PB85-119287

Westvaco Luke, Maryland Monitoring Program Data Analysis and Disperson Model Validation

Cramer (H.E.) Co., Inc., Salt Lake City, UT

Prepared for

Environmental Protection Agency
Philadelphia, PA

Jun 83

U.S. Department of Commerce
National Technical Information Service
NTIS

PB85-119287

EPA-903/9-83-002
June 1983

WESTVACO LUKE, MARYLAND MONITORING PROGRAM: DATA ANALYSIS AND DISPERSION MODEL VALIDATION
(Final Report)

Prepared By:

J. F. Bowers, H. E. Cramer,
W. R. Hargraves and A. J. Anderson

EPA Contract No. 68-02-3577
Modification No. 2

Project Officer

Alan J. Cimorelli
U. S. Environmental Protection Agency, Region III
Curtis Building
Sixth and Walnut Streets
Philadelphia, PA 19106

H. E. Cramer company, inc.
UNIVERSITY OF UTAH RESEARCH PARK
POST OFFICE BOX 8049
SALT LAKE CITY, UTAH 84108

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U.S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA-903/9-83-002	2.	3. RECIPIENT'S ACCESSION NO. PB85 119287
4. TITLE AND SUBTITLE Westvaco Luke, Maryland Monitoring Program: Data Analysis and Dispersion Model Validation (Final Report)		5. REPORT DATE June 1983 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) J. F. Bowers, H. E. Cramer, W. R. Hargraves and A. J. Anderson		8. PERFORMING ORGANIZATION REPORT NO. TR-83-153-01
9. PERFORMING ORGANIZATION NAME AND ADDRESS H. E. Cramer Company, Inc. P. O. Box 8049 Salt Lake City, UT 84108		10. PROGRAM ELEMENT NO. 11. CONTRACT/GRANT NO. Contract No. 68-02-3577 Modification No. 2
12. SPONSORING AGENCY NAME AND ADDRESS U. S. Environmental Protection Agency, Region III 6th and Walnut Streets Philadelphia, Pennsylvania 19106		13. TYPE OF REPORT AND PERIOD COVERED Final: July 1981-Feb 1983 14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

16. ABSTRACT

The Westvaco data set consists of detailed records of hourly emissions, meteorological and SO_2 air quality data collected in the vicinity of the Westvaco Corporation Paper Mill at Luke, Maryland during the period December 1979 through November 1981. The purpose of the Westvaco monitoring program was to acquire the data needed to select the most appropriate complex terrain dispersion model for use in establishing an SO_2 emission limitation for the Luke Mill. The major objectives of the work described in this report were to: (1) analyze and evaluate the Westvaco meteorological and air quality data in order to develop the most suitable data set to evaluate complex terrain dispersion models; and (2) use the Westvaco data set to evaluate the performance of EPA's Valley, Complex I and Complex II models, the H. E. Cramer Company's SHORTZ model and Westvaco Corporation's Luke Mill Model (LUMM). The results of the model performance evaluation support the use of the Valley, Complex I and Complex II models as safe-sided screening models when little or no onsite meteorological data are available. The SHORTZ and LUMM models provided accurate and unbiased estimates of the 25 highest 1-hour, 3-hour and 24-hour average concentrations at some of the monitors and systematically biased estimates at the other monitors. Based on the terms of a model evaluation protocol, the LUMM model was selected for use in establishing an SO_2 emission limitation for the Luke Mill.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Air Pollution Turbulent Diffusion Meteorology Mathematical Models Computer Models	Dispersion Models Complex Terrain Valley Model Complex I Model Complex II Model SHORTZ Model	

18. DISTRIBUTION STATEMENT Release Unlimited	19. SECURITY CLASS *(This Report)* Unclassified	21. NO. OF PAGES
	20. SECURITY CLASS *(This page)* Unclassified	22. PRICE

EPA Form 2220-1 (9-73)

DISCLAIMER

This report was furnished to the Environmental Protection Agency by H. E. Cramer Company, Inc., University of Utah Research Park, P. O. Box 8049, Salt Lake City, Utah 84108, in fulfillment of Contract No. 68-02-3577, Modification No. 2. The contents of this report are reproduced herein as received from H. E. Cramer Company, Inc. The opinions, findings and conclusions expressed are those of the authors and not necessarily those of the Environmental Protection Agency.

EXECUTIVE SUMMARY

BACKGROUND AND PURPOSE

The Westvaco data set consists of detailed records of hourly emissions, meteorological and SO_2 air quality data collected in the vicinity of the Westvaco Corporation Paper Mill at Luke, Maryland during the 2-year period December 1979 through November 1981. The purpose of the Westvaco monitoring program was to acquire the data needed to select the most appropriate complex terrain dispersion model for use in establishing an SO_2 emission limitation for the Luke Mill. The major objectives of the work performed by the H. E. Cramer Company, Inc. under Contract No. 68-02-3577 (Modification No. 2) with the U. S Environmental Protection Agency (EPA) were to: (1) analyze and evaluate the Westvaco meteorological and air quality data in order to develop the most suitable data set to evaluate complex terrain dispersion models; and (2) use the Westvaco data set to evaluate the performance of the SHORTZ, Valley, Complex I and Complex II complex terrain dispersion models. The site-specific Luke Mill Model (LUMM), which was developed for Westvaco Corporation by Environmental Research & Technology, Inc. (ERT), was subsequently added to the model performance evaluation. The purpose of this report is to summarize the H. E. Cramer Company's data analysis and model evaluation studies. The model performance evaluation for the SHORTZ and LUMM models described in this report was the first operational model performance evaluation to follow procedures of the type suggested in the August 1981 EPA report "Interim Procedures for Evaluating Air Quality Models."

DESCRIPTION OF THE WESTVACO MONITORING PROGRAM

The 2-year Westvaco monitoring program was conducted for Westvaco Corporation by ERT. Figure I is a topographic map of the area surrounding the Westvaco Luke Mill. The ⊚ symbol shows the location of the 190-meter

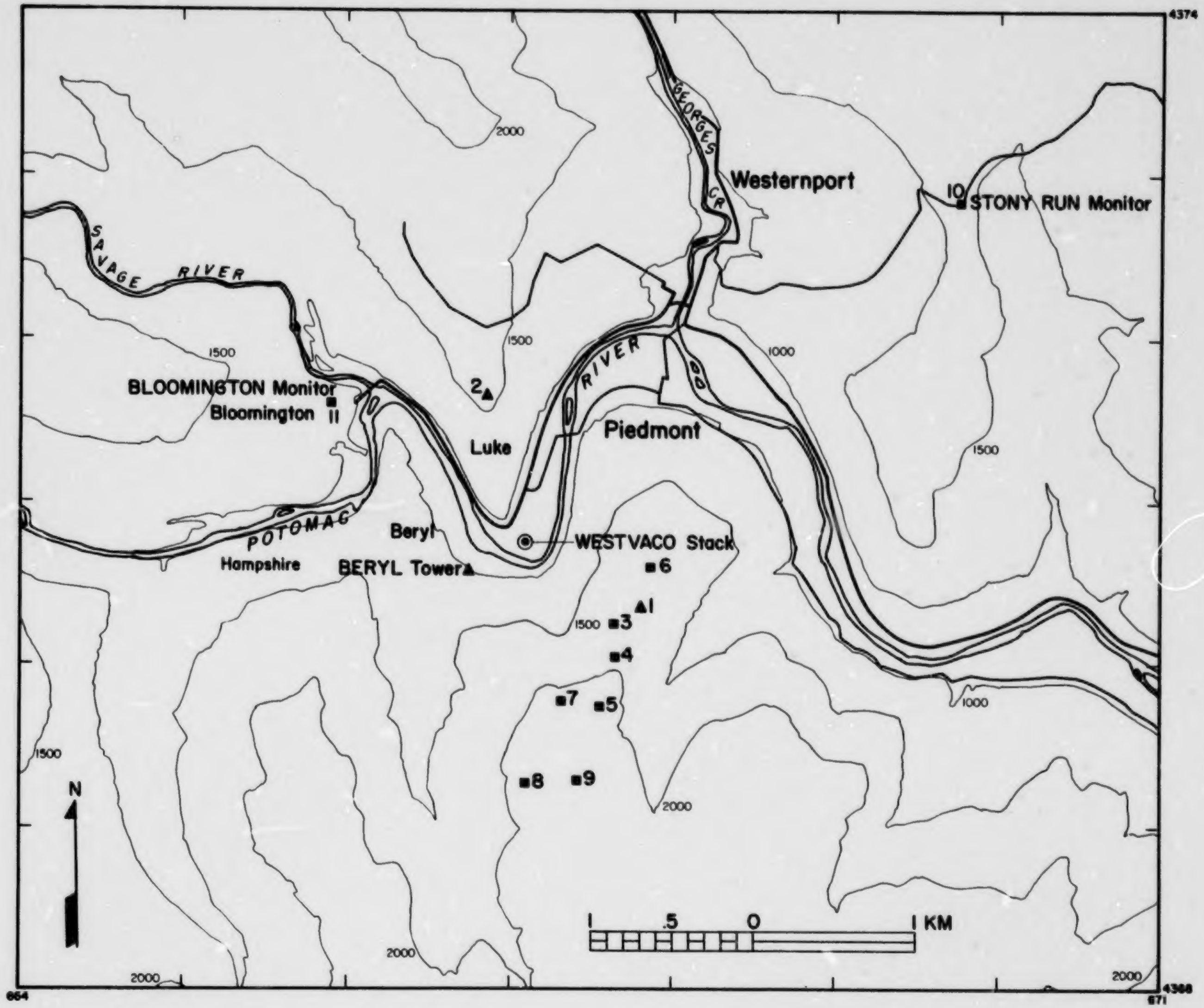
4374
2000
SAVAGE RIVER
GEORGES CR
Westernport
10
STONY RUN Monitor
1500
1000
BLOOMINGTON Monitor
Bloomington
II
2
Luke
RIVER
Piedmont
1500
POTOMAC
Beryl
Hampshire
BERYL Tower
WESTVACO Stack
6
1
1500
3
4
7
5
1000
8
9
2000
1500
N
1
.5
0
1 KM
2000
2000
2000
664
671
4368

FIGURE I. Topographic map of the area surrounding the Westvaco Luke Mill. Elevations are in feet above mean sea level (MSL) and the contour interval is 500 feet (150 meters). The ■ symbols represent SO_2 monitoring sites. The ▲ symbols represent meteorological monitoring sites. Sites 1 and 2 are also SO_2 monitoring sites.

Westvaco Main Stack, the ■ symbols show the locations of continuous SO_2 monitors and the ▲ symbols show the locations of the 100-meter Meteorological Tower No. 1, the 30-meter Meteorological Tower No. 2 (the Luke Hill Tower) and the 100-meter Beryl Meteorological Tower. (The wind and turbulence measurements from the Beryl Tower were not used in the study described in this report because the tower was so sheltered by the topography that the hourly vector average winds were reported as calm or variable more than one-third of the time.) Continuous SO_2 monitors were colocated with Tower No. 1 and Tower No. 2 and an acoustic sounder was colocated with Tower No. 2. As shown by Figure I, there were eleven SO_2 monitors of which eight were located on a ridge southeast of the Main Stack.

DESCRIPTION OF THE DISPERSION MODELS EVALUATED

The EPA Valley, Complex I and Complex II complex terrain dispersion models are all based on the steady-state Gaussian plume assumption. The Valley model is a screening model that uses hypothetical short-term meteorological inputs to calculate maximum 24-hour average concentrations produced by stack emissions in complex terrain. In the Valley Model, it is assumed that the plume is confined in an elevated stable layer within a 22.5-degree sector for 6 hours during a 24-hour period and that the plume directly impinges on any terrain at the same elevation as the plume height. The Complex I model is similar in form to the Valley model, but is designed to use actual hourly meteorological inputs. For the "worst-case" meteorological conditions assumed by the Valley model (6 hours of light winds and very stable conditions), the Complex I and Valley models give equivalent results. For hours with neutral or unstable conditions, the Complex I model assumes that the plume height above a receptor on elevated terrain is given by the maximum of: (1) half the plume height above plant grade, and (2) the plume height above plant grade minus half the receptor height above plant grade. The Complex II model is identical to the Complex I model except that the hourly lateral concentration distribution is assumed to be Gaussian rather uniform within a 22.5-degree sector. The Valley, Complex I and Complex II models use Pasquill-Gifford dispersion coefficients to estimate vertical and lateral (Complex II model only) plume dimensions. The versions of the Valley, Complex I and Complex II models used in the Westvaco model evaluation study were the versions contained in the EPA UNAMAP-4 series of models.

The SHORTZ and LUMM complex terrain dispersion models are steady-state bivariate Gaussian plume models that are similar in form to the Complex II model. Unlike the Valley, Complex I and Complex II models, the SHORTZ and LUMM models do not assign plume dimensions on the basis of discrete Pasquill stability categories. Instead, the two models use onsite turbulence and vertical wind-direction shear measurements as direct predictors of plume expansion. However, the two models differ in their wind-shear coefficients and in the assumed functional relationships between lateral and vertical turbulent intensities and lateral and vertical plume expansion. If a plume is contained within the surface mixing layer (as defined by the SHORTZ model) under any stability, the SHORTZ model assumes that the plume can impinge on elevated terrain at plume height. This is the same assumption as made by the Valley, Complex I and Complex II models under stable conditions only. The SHORTZ model assumes that a plume contained in an elevated stable layer above the top of the surface mixing layer does not significantly affect ground-level concentrations at any receptors, including receptors on terrain that extends into the elevated stable layer. In the LUMM model, under neutral or unstable conditions, it is assumed that the plume height increases as the plume passes over elevated terrain in a manner very similar to that assumed in the Complex I and Complex II models. Under stable conditions with the plume below a critical streamline height, the LUMM model assumes that the plume directly impinges on terrain at plume height. Unlike the Valley, Complex I, Complex II and SHORTZ models, the LUMM model assumes that only a portion of the plume is effectively reflected by the underlying terrain under stable conditions.

ANALYSES OF METEOROLOGICAL AND AIR QUALITY DATA

The H. E. Cramer Company reviewed and evaluated the concurrent meteorological and SO_2 air quality data from the Westvaco monitoring program as the data were received on a quarterly basis. Our analyses focused on examinations of concurrent meteorological and air quality data for the short-term periods during each quarter with the highest observed ground-level concentrations. These analyses indicated that the observed hourly ground-level concentration patterns often were not consistent with the straight-line transport of the plume from the Westvaco Main Stack to the monitoring network if the wind direction from any level of Tower No. 1 or Tower No. 2 was assumed to be representative of the transport wind direction. Additionally, differences in wind direction between the two towers as large as 180 degrees were not uncommon. The lateral plume dimensions inferred from some of the more coherent hourly ground-level concentration patterns were usually much larger than indicated by the lateral turbulent intensity at any tower and appeared to reflect the effects of the wind-direction shear, encountered by the buoyant plume within a transport distance of less than 1 kilometer, as the plume rose from the highly channeled valley flow through a transition layer to the synoptic scale winds above the ridgelines. Because of these unusually large vertical wind-direction shears, the H. E. Cramer Company (January 1981) recommend to EPA Region III that the Cramer, et al. (1972) wind-shear term be added to the SHORTZ model for application at the Luke Mill.

We noticed in our examination of the concurrent meteorological and air quality data that the highest short-term concentrations at the monitors south of the Westvaco Main Stack (Monitors 7, 8 and 9 in Figure I) tended to occur during stagnant periods with light winds and large vertical wind-direction shears. In general, the hourly SO_2 concentration patterns were chaotic and did not reflect the presence of a well-defined plume. We hypothesized that these concentrations are explained by one or more of the following factors: (1) curvilinear plume trajectories, (2) plume deformation by wind shear, and (3) previously emitted emissions advected back over the monitors by a wind shift. However, we question whether the sequence of events and the physical processes associated with the occurrence of the highest short-term concentrations at Monitors 7, 8 and 9 can ever be firmly established using the archived hourly average meteorological and air quality data.

In addition to tower wind measurements that are not necessarily representative of transport winds, we identified several other limitations in the Westvaco data set. As indicated in the above descriptions of the SHORTZ and LUMM models, onsite turbulence measurements are critical meteorological inputs to both models. For the first year of the Westvaco monitoring program, about 50 percent of the turbulence measurements at Tower No. 1 and 35 percent of the turbulence measurements at Tower No. 2 are missing. In our opinion, the use in the performance evaluation of the SHORTZ and LUMM models of an inordinate number of turbulence data substitutions and climatological turbulent intensities would raise serious questions about the validity of any conclusions that might be reached. We therefore recommended to EPA Region III that the model performance evaluation be restricted to the second year of the Westvaco monitoring program. Based on our comparison of the limited number of minisonde temperature soundings taken at the Luke Mill with the concurrent onsite tower temperature data, the onsite acoustic sounder mixing depths and the Greater Pittsburgh Airport rawinsonde soundings, we concluded that the acoustic sounder mixing depths were invalid. ERT independently arrived at the same conclusion about the validity of the acoustic sounder mixing depths. Calibration problems were found with the acoustic sounder during an independent quality assurance audit (Radian Corporation, January 1982), and these problems appear to be the most likely explanation for the invalid acoustic sounder mixing depths.

The air quality monitors with the highest observed concentrations during the 2-year Westvaco monitoring program were the monitors on the ridge southeast of the Main Stack (Monitors 1, 3, 4, 5, 6, 7, 8 and 9).

Because the distances from the Main Stack to these monitors range from 0.7 to 1.5 kilometers, the Westvaco data set principally reflects the concentrations at these relatively short distances. Monitor 10, which is on elevated terrain 3.4 kilometers northeast of the Main Stack, is of particular importance because it is the only monitor at the typical distance from the Main Stack to the Westvaco property boundaries. The two remaining monitors (Monitors 2 and 11) are not of major interest for the purpose of dispersion model evaluation for two reasons. First, these monitors generally had the lowest observed concentrations. Second, the distances from the Main Stack to these monitors were within the distance range for the monitors in the sector on the ridge southeast of the Main Stack. We therefore recommended to EPA Region III that the model performance evaluation consider Monitors 1, 3, 4, 5, 6, 7, 8, 9 and 10.

RESULTS OF THE MODEL PERFORMANCE EVALUATION

We began the model performance evaluation using the Valley model. The emissions data used in the Valley model calculations were for the calendar days during each year of the 2-year Westvaco monitoring program with the highest and second-highest observed 24-hour average concentrations at the nine monitoring sites selected for use in the model performance evaluation. The meteorological conditions assumed for the 6 hours of plume impingement in the Valley model calculations were F stability and a mean wind speed of 2.5 meters per second. With the exception of Monitor 10, the Valley model overpredicted the highest and second-highest observed 24-hour average concentrations by factors of 3 to 16. Under the assumed "worst-case" meteorological conditions, the Westvaco plume does not mix far enough downward in the Valley model calculations to cause a non-zero concentration at Monitor 10. In a regulatory application of the Valley model at the Luke Mill, all elevated terrain at and beyond the boundaries of the Westvaco property would be considered in the model analysis. Monitors 8 and 9 are on elevated terrain near the southern boundary of the Westvaco property, and the bias toward overestimation at these monitors tends to support the continued use of the Valley model as a safe-sided screening model.

As discussed above, the Valley and Complex I models are based on very similar assumptions. If the wind is contained within a 22.5-degree sector for 6 hours of a 24-hour period and the meteorological conditions during these 6 hours consist of F stability and an average wind speed of 2.5 meters per second, the 24-hour average concentrations calculated by the two models at receptors in the downwind 22.5-degree sector are equivalent. Because of the conservativeness of the Valley model for the Westvaco data set, it follows that the Complex I model should also be a safe-sided screening model for the Westvaco data set. The Complex II model predicts higher hourly concentrations than the Complex I model because the crosswind concentration distribution is assumed to be Gaussian (as described by Pasquill-Gifford lateral dispersion coefficients) rather than uniform within a 22.5-degree sector. Consequently, the Complex II model should also be safe-sided screening model for the Westvaco data set. Of the five complex terrain dispersion models described above, only the generalized SHORTZ and site-specific LUMM models were considered to be likely candidates as refined (non-screening) models. It was therefore the joint decision of the H. E. Cramer Company and the EPA Project Officer that the detailed model performance evaluation should be restricted to the SHORTZ and LUMM models.

On 21 October 1982, Westvaco Corporation, the State of Maryland, EPA Region III and the EPA Office of Air Quality Planning and Standards (OAQPS) agreed to a protocol for the evaluation of the SHORTZ and LUMM dispersion models using the data from the second year of the Westvaco monitoring program. This protocol, which was based in part on the procedures suggested in the August 1981 EPA report "Interim Procedures for Evaluating Air Quality Models," identified various measures of model performance and assigned to these measures numerical values (points) dependent on the objectives of the model calculations. Because the objective of the model performance evaluation was to select the most appropriate model to establish an SO_2 emission limitation for the Westvaco Main Stack, the model evaluation protocol placed emphasis on the ability of the models to predict the highest

1-hour, 3-hour and 24-hour average concentrations paired in space only at the nine monitors of concern. The scoring system for each pairing of observed and calculated concentrations was based on: (1) the differences between the observed and calculated concentrations, and (2) the correspondence between the variances of the observed and calculated concentrations. Under the terms of the protocol, the model with the highest score was to be used to establish the SO_2 emission limitation for the Main Stack. A copy of the 21 October 1982 model evaluation protocol is contained in Appendix A of this report. Westvaco Corporation, the State of Maryland and EPA also agreed on 21 October 1982 that: (1) The hourly meteorological inputs used in the SHORTZ model calculations would be the inputs recommended by the H. E. Cramer Company; (2) The hourly meteorological inputs used in the LUMM model calculations would be the inputs recommended by ERT; (3) ERT would conduct the performance evaluation; and, (4) The H. E. Cramer Company would independently review the results of ERT's SHORTZ model calculations and would verify ERT's computation of scores for the SHORTZ and LUMM models.

Table I summarizes the qualitative performance of the SHORTZ and LUMM models by monitor. At the six monitoring sites between 0.7 and 1.1 kilometers from the Main Stack, the LUMM model closely matched the 25 highest observed short-term SO_2 concentrations, while the SHORTZ model systematically overestimated these concentrations. For example, the cumulative frequency distributions of the 25 highest observed and calculated 24-hour average concentrations at Monitor 1 are compared in Figure II for the SHORTZ model and in Figure III for the LUMM model. On the other hand, at the three monitoring sites between 1.5 and 3.4 kilometers from the Main Stack, the SHORTZ model closely matched the 25 highest observed short-term SO_2 concentrations, while the LUMM model systematically underestimated these concentrations. To illustrate relative model performance at the three most distant monitors, Figure IV compares the cumulative frequency distributions of the 25-highest observed and calculated 24-hour average concentrations at Monitor 10 for the SHORTZ model and Figure V compares these distributions for the LUMM model. Although the results of the model performance evaluation qualitatively summarized in Table I appear to show a distance dependence in

TABLE I

SUMMARY OF MODEL PERFORMANCE BY MONITORING SITE

Monitor	Distance from Main Stack (km)	Elevation Above Main Stack Top (m)	Model with Highest Score
1	0.8	126	LUMM
3	0.7	86	LUMM
4	0.9	125	LUMM
5	1.1	161	LUMM
6	0.8	113	LUMM
7	1.0	159	LUMM
8	1.5	165	SHORTZ
9	1.5	195	SHORTZ
10	3.4	26	SHORTZ

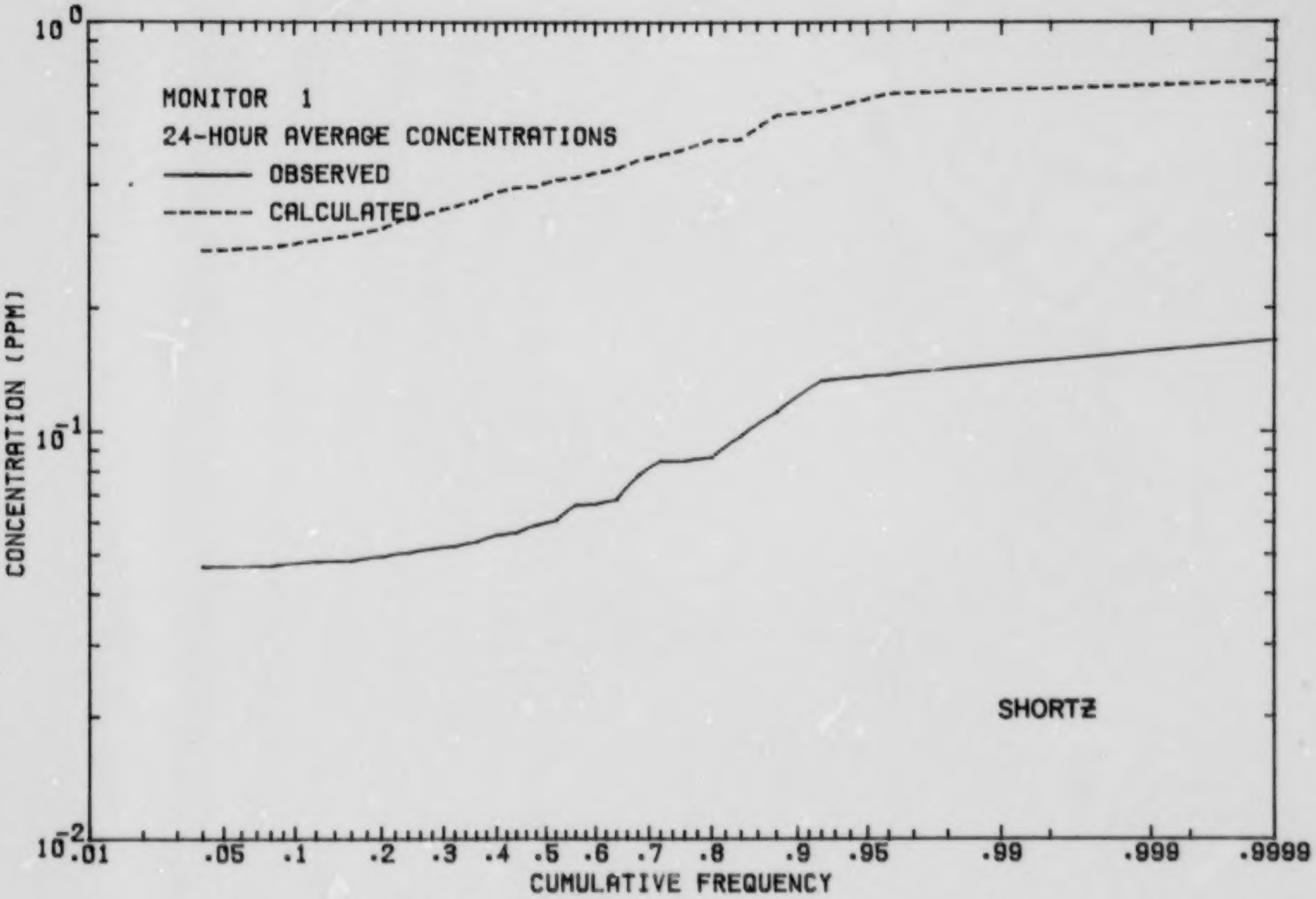

Figure II. Comparison of the cumulative frequency distribution of the 25 highest observed (minus background) 24-hour average SO_2 concentrations at Monitor 1 during the second year of the Westvaco monitoring program with the cumulative frequency distribution of the 25 highest 24-hour average concentrations calculated by SHORTZ.

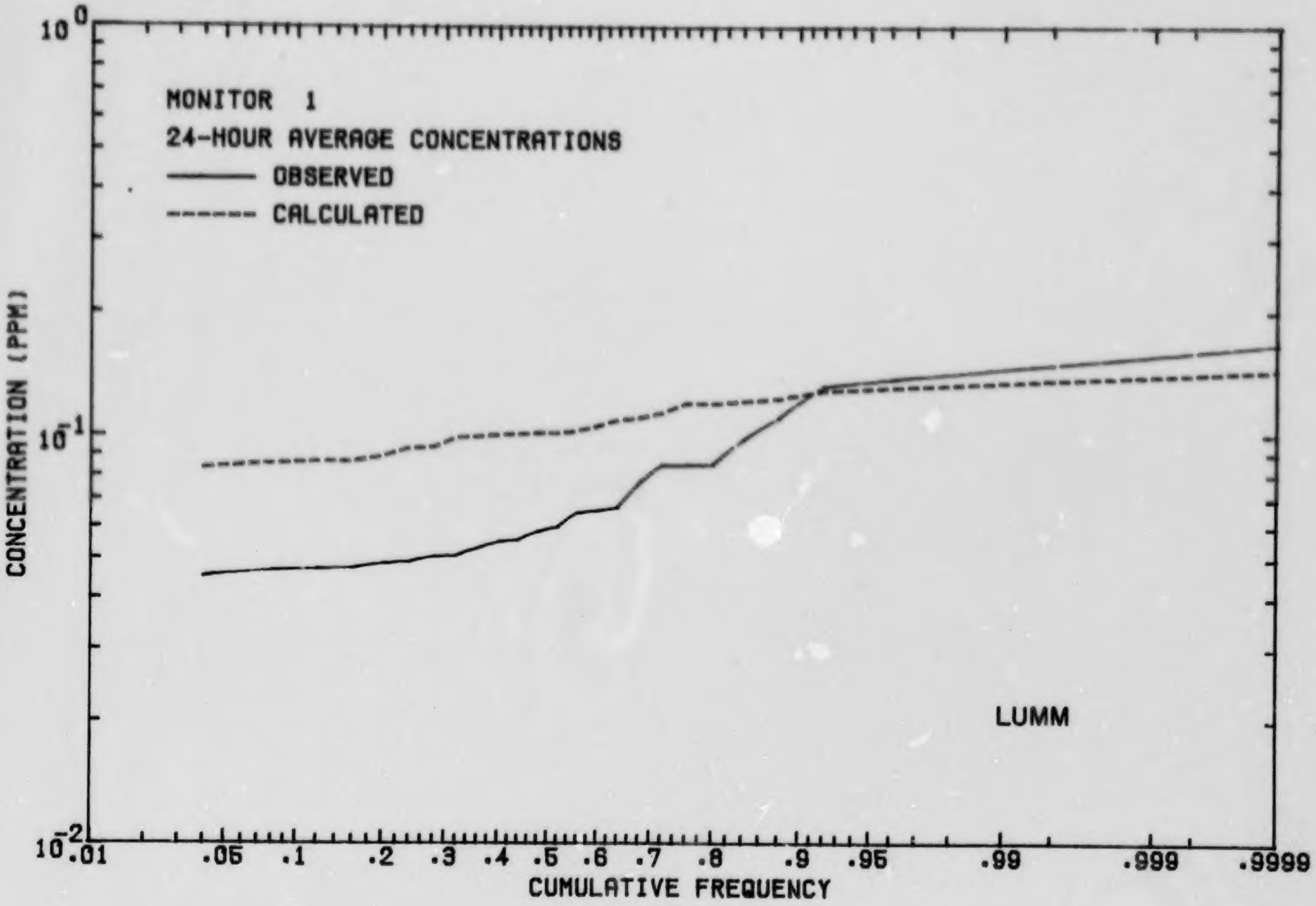

Figure III. Comparison of the cumulative frequency distribution of the 25 highest observed (minus background) 24-hour average SO_2 concentrations at Monitor 1 during the second year of the Westvaco monitoring program with the cumulative frequency distribution of the 25 highest 24-hour average concentrations calculated by LUMM.

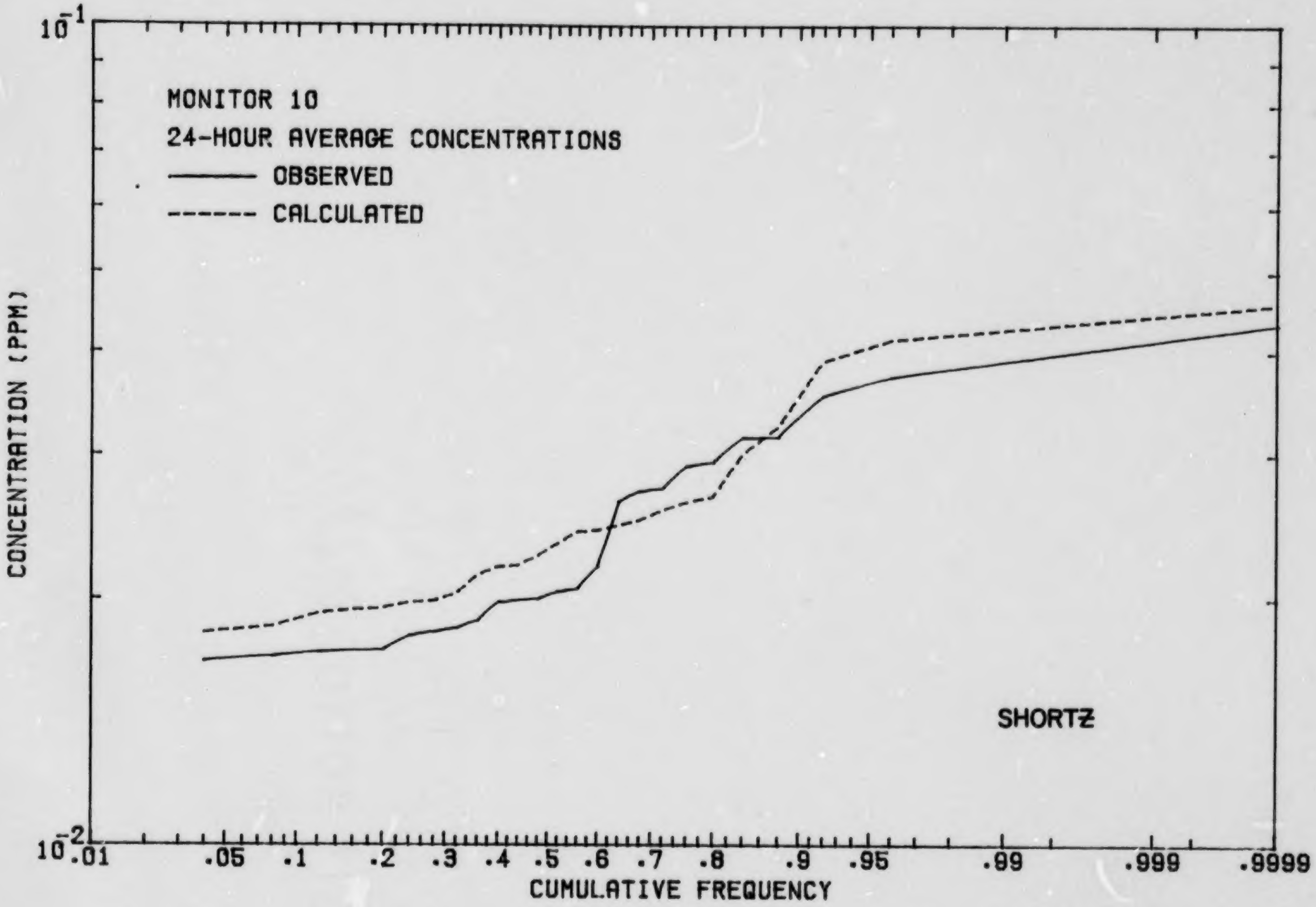

Figure IV. Comparison of the cumulative frequency distribution of the 25 highest observed (minus background) 24-hour average SO_2 concentrations at Monitor 10 during the second year of the Westvaco monitoring program with the cumulative frequency distribution of the 25 highest 24-hour average concentrations calculated by SHORTZ.

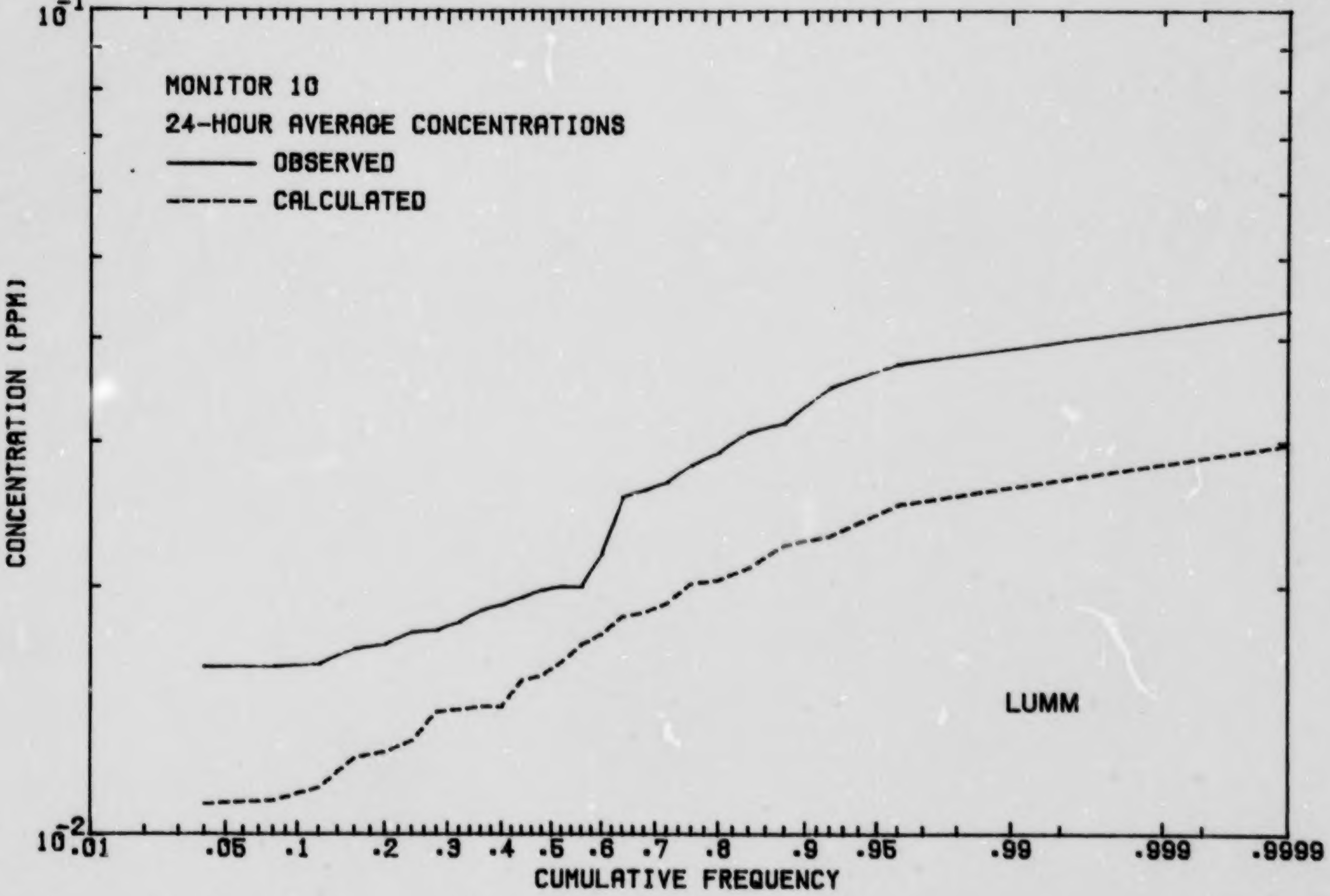

Figure V. Comparison of the cumulative frequency distribution of the 25 highest observed (minus background) 24-hour average SO_2 concentrations at Monitor 10 during the second year of the Westvaco monitoring program with the cumulative frequency distribution of the 25 highest 24-hour average concentrations calculated by LUMM.

model performance, the results do not show any clear trend according to elevation above the top of the Main Stack. The SHORTZ model had the highest score at the monitors with both the highest and lowest elevations. Because the LUMM model had the highest score at six out of the nine monitors of concern, the LUMM model had the highest overall score by about a factor of 2. Under the terms of the model evaluation protocol, the LUMM model was therefore selected to determine an SO_2 emission limitation for the Luke Mill.

RESULTS OF THE EMISSION LIMITATION CALCULATIONS

ERT used the LUMM model to estimate an SO_2 emission limitation for the Westvaco Main Stack of 75.1 tons per day under the assumption that the only constraint is compliance with the National Ambient Air Quality Standards (NAAQS) for SO_2. In the absence of the data from the 2-year Westvaco monitoring program and the model performance evaluation, the SO_2 emission limitation for the Main Stack would probably be determined by EPA on the basis of predictions made using the Complex I model with any available onsite meteorological data. To gain insight to the differences in emission limitations arising from the two different (screening and refined) modeling approaches, we used the Complex I model with the source and meteorological data from the second year of the Westvaco monitoring program to estimate an emission limitation. Under the assumption that compliance with the NAAQS is the only constraint, the results of the Complex I model calculations indicate that the emission limitation should be 29.9 tons per day, which is a factor of 2.5 lower than the emission limitation estimated using the LUMM model.

CONCLUSIONS

In our opinion, the Westvaco data set is the most detailed and best documented data set developed to date for the purpose of evaluating and validating complex terrain dispersion models. However, we believe that the Westvaco Luke Mill modeling problem is sufficiently unique that any conclusions about the accuracy of dispersion models evaluated using the Westvaco data set should be used with caution unless they are supported by previous (and/or future) experience in testing the models in complex terrain. The complex terrain dispersion models evaluated in the study described in this report can be divided into two general categories: (1) screening models (the Valley, Complex I and Complex II models), and (2) refined models (the SHORTZ and LUMM models). The objective of the screening models is to provide safe-sided estimates of maximum short-term concentrations when little or no onsite meteorological data are available, while the objective of the refined models is to use onsite meteorological measurements to provide accurate and unbiased estimates of the highest short-term concentrations. Previous experience with the screening models, especially the Valley model, has supported their use as safe-sided screening tools in complex terrain. Although the Westvaco model performance evaluation is the most rigorous test to date of the SHORTZ model, the limited previous tests of the model during the last 8 years have supported its use as a refined complex terrain dispersion model. The LUMM model was specifically designed for application to the Westvaco data set and has no past experience.

The screening models satisfied the objective of providing safe-sided estimates of maximum short-term concentrations in the Westvaco model evaluation study. Consequently, we believe that these models may be considered to be state-of-the-art models for their intended application. The LUMM model closely matched the highest observed short-term SO_2 concentrations at the six monitors between 0.7 and 1.1 kilometers from the Westvaco Main Stack, while the SHORTZ model closely matched the highest observed short-term SO_2 concentrations at the three monitors between 1.5 and 3.4 kilometers from the Main Stack. The performance of the LUMM and SHORTZ models for the Westvaco data set appears to be a function only of distance from the Main Stack; the SHORTZ model had the best quantitative performance at the monitors with both the lowest and highest elevations above the stack top. Assuming that the typical distance to plume stabilization is on the order of ten stack heights (Briggs, 1969), one possible interpretation of the results of the Westvaco model performance evaluation is that the LUMM model is the state-of-the-art refined model at distances less than the distance to plume stabilization and the SHORTZ model is the state-of-the-art refined model at longer downwind distances. We conclude from the results of the model performance evaluation that: (1) both the LUMM and SHORTZ models are state-of-the-art refined models for the Westvaco data set, and (2) under the terms of the 21 October 1982 model evaluation protocol, the LUMM model should be used to establish an SO_2 emission limitation for the Westvaco Main Stack. In our opinion, there are too many ambiguities in the Westvaco data set and the results of the performance evaluation for the LUMM and SHORTZ models to resolve differences in modeling approaches between the two models such as plume-height adjustments ("plume path coefficients") and surface reflection coefficients. We believe that these modeling issues can only be resolved by additional model performance evaluation studies.

(This Page Intentionally Blank)

TABLE OF CONTENTS

Section	Title	Page
	EXECUTIVE SUMMARY	iii
1	INTRODUCTION	1
	1.1 Background and Purpose	1
	1.2 Report Organization	4
2	DESCRIPTION OF THE DISPERSION MODELS EVALUATED	7
3	RESULTS OF THE DATA ANALYSES, THE MODEL PERFORMANCE EVALUATION AND THE EMISSION LIMITATION CALCULATIONS	15
	3.1 Results of the Meteorological and Air Quality Data Analyses	15
	3.2 Results of the Model Performance Evaluation	32
	3.3 Results of the SO_2 Emission Limitation Calculations	53
4	CONCLUSIONS	61
	REFERENCES	67
Appendix		
A	MODEL EVALUATION PROTOCOL	A-1
B	ANALYSIS OF OBSERVED HOURLY SO_2 CONCENTRATIONS	B-1
C	RESULTS OF THE SHORTZ MODEL CONCENTRATION CALCULATIONS	C-1
D	CUMULATIVE FREQUENCY DISTRIBUTIONS OF THE 25 HIGHEST OBSERVED (MINUS BACKGROUND) AND CALCULATED (SHORTZ) SHORT-TERM SO_2 CONCENTRATIONS	D-1

TABLE OF CONTENTS (Continued)

Appendix	Title	Page
E	CUMULATIVE FREQUENCY DISTRIBUTIONS OF THE 25 HIGHEST OBSERVED (MINUS BACKGROUND) AND CALCULATED (LUMM) SHORT-TERM SO_2 CONCENTRATIONS	E-1
F	DETAILED DESCRIPTION OF THE DISPERSION MODELS EVALUATED	F-1
	F.1 Description of the SHORTZ Model	F-1
	F.2 Description of the Valley Model	F-14
	F.3 Description of the Complex I and Complex II Models	F-17
	F.4 Description of the LUMM Model	F-22

SECTION 1
INTRODUCTION

1. BACKGROUND AND PURPOSE

On 16 July 1975, the State of Maryland submitted to the U. S. Environmental Protection Agency (EPA) Region III a proposed revision to the Maryland State Implementation Plan (SIP) for the attainment and maintenance of the National Ambient Air Quality Standards (NAAQS). The proposed revision consisted of a request to grant an exemption to the Westvaco Corporation Paper Mill at Luke, Maryland from Maryland's fuel sulfur content regulation (10.03.36.04B) which did not allow the use of fuel containing more than 1 percent sulfur by weight. The purpose of the request for an exemption was to allow the Westvaco Mill to burn coal with a sulfur content above 1 percent. On behalf of Westvaco Corporation, the State of Maryland submitted a dispersion model analysis intended to demonstrate that the requested exemption would not result in violations of the NAAQS for sulfur dioxide (SO_2). Following review of the analysis, EPA concluded that the analysis underestimated the impact of SO_2 emissions and did not demonstrate that the NAAQS for SO_2 would be attained or maintained if the exemption were to be approved as a SIP revision. EPA also concluded that attempts to resolve deficiencies the Agency believed to exist in Westvaco's modeling demonstration would be futile and that it would be desirable to validate a complex terrain dispersion model for use in the final rule making decision. An amended consent order, submitted to EPA by the State of Maryland, allowed the Westvaco Mill to burn coal with a sulfur content above 1 percent for a 2-year period during which Westvaco was required to install and operate an extensive air quality and meteorological monitoring network. The purpose of the monitoring program was to acquire the data needed to validate a dispersion model to be used in the final rule making decision.

The 2-year Westvaco Luke Mill monitoring program (December 1979 through November 1981) was conducted for Westvaco Corporation by Environmental Research & Technology, Inc. (ERT). Figure 1-1 is a topographic map

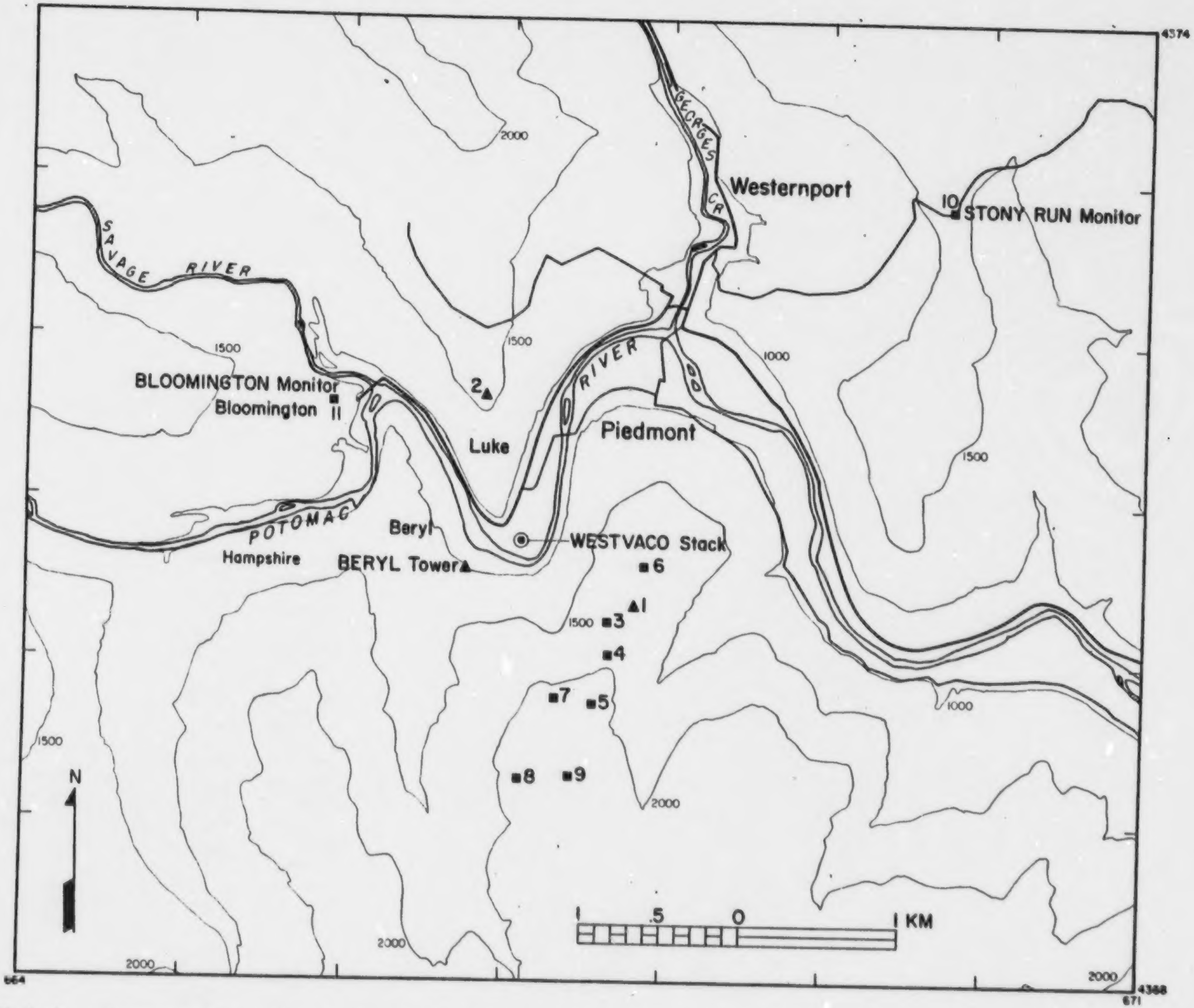
4374
2000
Westernport
GEORGES CR
10
STONY RUN Monitor
SAVAGE RIVER
1500
1500
RIVER
1000
BLOOMINGTON Monitor
Bloomington
11
2
Luke
Piedmont
1500
POTOMAC
Beryl
WESTVACO Stack
Hampshire
BERYL Tower
6
1
1500
3
4
7
5
1000
1500
N
8
9
2000
.5
0
1 KM
2000
2000
2000
664
4368
671

FIGURE 1-1. Topographic map of the area surrounding the Westvaco Luke Mill. Elevations are in feet above mean sea level (MSL) and the contour interval is 500 feet (150 meters). The ■ symbols represent SO_2 monitoring sites. The ▲ symbols represent meteorological monitoring sites: Sites 1 and 2 are also SO_2 monitoring sites.

of the area surrounding the Westvaco Luke Mill that shows the locations of the Main Stack, the SO_2 air quality monitors and the instrumented meteorological towers used during the Westvaco monitoring program. A detailed description of the Westvaco monitoring program is given in the report by Hanna, et al. (1982a). The Hanna, et al. (1982a) report also discusses the development for Westvaco Corporation of the site-specific Luke Mill Model (LUMM).

In July 1981, EPA contracted with the H. E. Cramer Company, Inc. of Salt Lake City, Utah to provide an independent review and assessment of the Westvaco data set and to perform complex terrain dispersion model validation studies. The specific tasks of EPA contract No. 68-02-3577 (Modification No. 2) may be summarized as follows:

- Task I - Analyze and evaluate the concurrent emissions, meteorological and SO_2 air quality data collected during the 2-year Westvaco monitoring program and recommend the data set most appropriate for complex terrain dispersion model validation studies

- Task II - Conduct a performance evaluation of the SHORTZ model (Cramer, et al., 1975; Bjorklund and Bowers, 1982), the Valley Model (Burt, 1977) and the Complex I and II models (undocumented)

- Task III - Provide an independent technical review of all work submitted by or on behalf of Westvaco Corporation in support of an appropriate emission limitation for the Luke Mill

- Task IV - Using the model determined in Task II as being the most appropriate for predicting maximum short-term concentrations, estimate the SO_2 emission limitation required to maintain the NAAQS in the vicinity of the Luke Mill

- Task V - As requested, assist in resolving differences of opinion on technical issues between EPA and Westvaco Corporation
- Task VI - Prepare a final report summarizing the results of the data analysis and model validation efforts

The purpose of this report is to provide EPA with a summary of the H. E. Cramer Company's data analysis and model validation efforts using the Westvaco data set (Task VI). Most of the information presented in this report has been previously provided to EPA Region III in the form of monthly progress reports submitted to the EPA Project Officer during the 19-month period of performance for the technical effort. The requirements of Task III are addressed in separate reports by Cramer and Bowers (1982) and Bowers and Hargraves (1982). To satisfy the requirements of Task V, representatives of the H. E. Cramer Company (Cramer and Bowers) met in Baltimore, Maryland on 8 September 1982 with representatives of EPA Region III, the EPA Office of Air Quality Planning and Standards (OAQPS) and the State of Maryland and on 20 September 1982 with representatives of EPA Region III, EPA OAQPS, the State of Maryland and Westvaco Corporation. Additional work under Task V was accomplished through numerous telephone conversations between the H. E. Cramer Company and the EPA Project Officer. This report contains the information specifically requested for the Task VI final report in the Scope of Work for EPA Contract No. 68-02-3577, Modification No. 2.

1.2 REPORT ORGANIZATION

In addition to the Introduction, this report consists of three major sections and six appendices. Section 2 briefly describes the complex terrain dispersion models evaluated using the Westvaco data set, including the site-specific Luke Mill Model (LUMM) developed for Westvaco Corporation by Hanna, *et al*. (1982a), and recommends modifications in the SHORTZ, Complex I and Complex II models for application to the Westvaco data set. The results of the data analysis, model validation and emission limitation studies are discussed in Section 3. Our conclusions, including an assessment of the implications of the work described in this report on the state of the art of complex terrain dispersion modeling, are presented in Section 4. As discussed in Section 3.2, the SHORTZ and LUMM models were selected for use in the final model performance evaluation because they were determined to be the two models most likely to be applicable at the Westvaco Luke Mill. The performance evaluation of the SHORTZ and LUMM models was performed following a protocol agreed upon in advance by EPA Region III, EPA OAQPS, the State of Maryland and Westvaco Corporation. This 21 October 1982 protocol is contained in Appendix A. The results of our detailed analysis of the Westvaco SO_2 air quality measurements are tabulated in Appendix B, the results of the SHORTZ model calculations are tabulated in Appendix C and graphically compared with the air quality observations in Appendix D, and the results of the LUMM model calculations (as reported by Hanna, et al., 1982b) are graphically compared with the air quality observations in Appendix E. Appendix F presents a detailed description of the assumptions and equations of the five complex terrain dispersion models evaluated using the Westvaco data set.

(This Page Intentionally Blank)

SECTION 2

DESCRIPTION OF THE DISPERSION MODELS EVALUATED

The following discussion of the SHORTZ, Valley, Complex I, Complex II and LUMM complex terrain dispersion models is restricted to the model features applicable to the Westvaco model evaluation effort. For example, the SHORTZ model is a highly generalized model that is designed to calculate the concentrations produced at a large number of receptors by emissions from a large number of stack, building and area sources. The following description of the SHORTZ model considers only the model's stack source option. The versions of the Valley, Complex I and Complex II models described below are the versions contained in the EPA UNAMAP-4 series of models.

The SHORTZ Model

The SHORTZ model uses the steady-state Gaussian plume equation for a continuous elevated source to calculate hourly ground-level concentrations. Plume rise is calculated using the Briggs (1969; 1971; 1972) equations for the final rise of a buoyant plume, modified by the Cramer, et al. (1975) stack-tip downwash correction. The method of image sources is used to account for multiple reflections of plume material at the earth's surface and at the top of the surface mixing layer. A wind-profile exponent law is used to adjust the mean wind speed from the measurement height to the stack height for use in the plume rise calculations and to the plume stabilization height for use in the concentration calculations. The SHORTZ model uses Cramer (1976) dispersion coefficients, which assume that lateral (vertical) plume expansion is directly proportional to the lateral (vertical) turbulent intensity or standard deviation of the wind azimuth (elevation) angle in radians. The Cramer (1976) dispersion coefficients utilize lateral and vertical virtual distances to account for the effects on initial dispersion of entrainment by the buoyant plume ("buoyancy induced dispersion"). At the downwind distance of plume stabilization, the SHORTZ model assumes Gaussian lateral and vertical concentration distributions with the radius of the plume equal to 0.5 times the plume rise. Because of the very large vertical wind-direction shears found to occur at times in the Westvaco tower wind measurements, the SHORTZ model was modified for use in the model performance evaluation to consider the effects of vertical wind-direction shear on lateral plume growth following the Cramer, et al. (1972) approach.

The SHORTZ model makes the following assumptions in complex terrain: (1) The top of the surface mixing layer is at a constant height above mean sea level; (2) The mean wind speed is a function of height above mean sea level; (3) Buoyant plumes that stabilize above the top of the surface mixing layer do not contribute to significant ground-level concentrations at any point, including terrain points that are also above the top of the surface mixing layer; (4) The centerline of a plume contained in the surface mixing layer remains at the plume stabilization height above mean sea level and is allowed to mix to the ground; (5) The centerline of a plume contained within the surface mixing layer that intersects a terrain elevation greater than the plume stabilization height is assumed to follow the terrain; and, (6) In order to prevent a physically unrealistic compression of plumes as they pass over elevated terrain, the effective mixing depth is not permitted to be less than a specified minimum value. It is important to note that the SHORTZ model's definition of the mixing depth is based on the vertical profile of the vertical turbulent intensity rather than on the vertical temperature profile. Zero is not a valid SHORTZ model mixing depth.

The Valley Model

The EPA Valley model is primarily designed to calculate maximum 24-hour average concentrations produced by stack emissions in complex terrain. The Valley model is a screening model and is intended for use with hypothetical rather than actual short-term meteorological inputs. The

Valley model is based on a modified version of the steady-state Gaussian plume equation for a continuous elevated source. The Briggs (1971; 1975) plume rise equations are used to calculate distance-dependent plume rise. The Valley model assumes that the plume is contained in an elevated stable layer and is confined within a 22.5-degree sector for 6 hours during a 24-hour period. The average horizontal concentration distribution within this sector is assumed to be uniform, eliminating the need for lateral dispersion coefficients. Vertical dispersion is assumed to be described by the Pasquill-Gifford vertical dispersion coefficients, modified to account for the effects of entrainment on the initial dispersion of a buoyant plume using procedures suggested by Pasquill (1976). The Valley model's treatment of the effects of entrainment differs from that of the SHORTZ model in two ways. First, the plume is assumed to have a uniform ("top hat") rather than a Gaussian concentration distribution prior to, and at the distance of, stabilization. Second, entrainment is accounted for through the addition of variances rather than through the use of virtual distances. The Valley model assumes that the plume directly impinges on any terrain at the height of the plume centerline during the 6 hours when it is contained in an elevated stable layer and confined within a 22.5-degree sector. Concentrations are interpolated to zero on terrain that extends 400 meters or more above the height of the plume centerline.

The Complex I and Complex II Models

The EPA Complex I and II models are screening models that are designed to use sequential hourly meteorological inputs to calculate ground-level concentrations in complex terrain. Under stable conditions, the equation used by the Complex I model to calculate hourly ground-level concentrations is the same as used by the Valley model after adjustment is made for the Valley model's assumption that essentially the same hourly concentration occurs for 6 hours in a 24-hour period. The Complex II model differs from the Complex I model only in that the lateral concentration distribution is Gaussian rather than uniform within a 22.5-degree sector. The Complex

II model uses Pasquill-Gifford lateral dispersion coefficients, modified to include the effects of entrainment in exactly the same manner as the vertical dispersion coefficients. During hours with neutral or unstable conditions, the Complex I and II models assume that the plume height above a receptor on elevated terrain is given by the maximum of: (1) half the plume height above plant grade, and (2) the plume height above plant grade minus half the receptor height above plant grade. The Complex I and II models contain a multiple reflection term to confine the plume within the surface mixing layer during hours with neutral or unstable conditions. The top of the surface mixing layer is assumed to be terrain following rather than at a constant height above mean sea level as assumed by the SHORTZ model. The Complex I and II models use a wind-profile exponent law to adjust the wind speed from the measurement height to the stack height for use in both the plume rise and concentration calculations. Wind speed is assumed to be a function of height above local ground level rather than of height above mean sea level as assumed by the SHORTZ model.

The H. E. Cramer Company made several modifications in the computer codes for the Complex I and II models to improve their performance for the Westvaco data set. First, because the original codes assume an adiabatic thermal stratification whenever the Pasquill stability category is neutral or unstable, they overestimate plume rise and underestimate ground-level concentrations if the actual thermal stratification is stable. We therefore modified the codes for the Complex I and II models to read the observed hourly vertical potential temperature gradients and to key the selection of the adiabatic or stable plume rise equation on the potential temperature gradient rather than on the Pasquill stability category. (The SHORTZ and LUMM models also follow this approach.) The original codes for the Complex I and II models accept sequential hourly SO_2 emission rates and calculate hourly stack exit velocities from a single input exit velocity under the assumption that the exit velocity is directly proportional to the emission rate. This assumption is not highly accurate for the Westvaco Main Stack because of variations in coal sulfur content. Also, the original codes do not allow for hour-to-hour variations in the stack exit temperature. We therefore modified the codes for the Complex I and II models to allow them to use actual hourly values of the stack exit velocity and exit temperature.

The LUMM Model

The LUMM and SHORTZ models have in common some basic model concepts such as the use of turbulence measurements as direct predictors of plume expansion. However, the two models differ in other concepts such as plume-height adjustments in complex terrain, surface reflection coefficients in complex terrain, and the forms of the lateral and vertical "universal functions" relating lateral and vertical turbulent intensities respectively to lateral and vertical plume expansion. Additionally, the LUMM model lacks a multiple reflection term to confine the plume within the surface mixing layer. To preclude underestimation of concentrations at the longer downwind distances where the restriction on vertical mixing at the top of the surface mixing layer becomes important, the LUMM model does not allow the vertical dispersion coefficient to exceed a maximum value. ERT used the Westvaco data set to evaluate six versions of the basic LUMM model, differing in model constants and/or meteorological inputs, to obtain the final version of the model with the best overall performance.

The LUMM model uses the same plume rise equations as the Complex I and II models. If the vertical potential temperature gradient is positive and the calculated stable plume rise is less than the corresponding calculated adiabatic plume rise, the LUMM model defines meteorological conditions as stable. "Neutral" conditions are assumed if the adiabatic plume rise is less than the corresponding stable plume rise or if the potential temperature gradient is less than or equal to zero. Unlike the SHORTZ model, which does not require any definition of stability categories, the LUMM model uses two stability categories (stable and "neutral") to select the appropriate vertical "universal function" for plume dispersion.

The LUMM and Complex II models use the same basic equation to calculate ground-level concentrations under "neutral" conditions except that the LUMM model does not include the multiple reflection term to confine the plume within the surface mixing layer. Based on a comparison by ERT of concurrent calculated and observed concentrations under "neutral" conditions for selected cases, the LUMM model defines the plume height above a receptor on elevated terrain under "neutral" conditions as the maximum of: (1) the plume height above plant grade multiplied by 0.4, and (2) the plume height above plant grade minus 0.6 times the receptor height above plant grade. This approach is very similar to the "half height" adjustment made by the Complex I and II models with neutral or unstable conditions. During hours with stable conditions, the height of a plume above a receptor on elevated terrain is assumed by the LUMM model to depend on the relationship between the plume height above plant grade and the height of a critical streamline above plant grade. The critical streamline height is a function of: (1) the maximum terrain height above plant grade in the downwind direction within 10 kilometers of the stack, (2) the mean wind speed, (3) the ambient air temperature, and (4) the vertical potential temperature gradient. If the plume height is above the critical streamline height, the "neutral" concentration equation is used by the LUMM model. If the plume height is below the critical streamline height, zero concentration is assumed at each receptor on terrain above the critical streamline height and two concentrations are calculated for each receptor below the critical streamline height. The first of these concentrations is obtained from the "neutral" concentration equation with the plume height above the receptor given by the maximum of: (1) zero, and (2) the difference between the plume height above plant grade and the receptor height above plant grade. The second concentration calculated by the LUMM model when the plume height is below the critical streamline height is obtained by modifying the "neutral" concentration equation in the following ways: (1) the plume height above the receptor is assumed to be zero (i.e., direct impingement is assumed), and (2) only 20 percent of the plume material is effectively assumed to be reflected by the underlying terrain (i.e., the site-specific surface reflection coefficient is assumed to be 1.2).

The LUMM model assumes that the lateral dispersion coefficient is comprised of components due to the effects of turbulence, the effects of entrainment by the buoyant plume and the effects of vertical wind-direction shear. Similarly, the LUMM model assumes that the vertical dispersion coefficient is comprised of components due to the effects of turbulence and the effects of entrainment by the buoyant plume. The total dispersion coefficients due to the combined effects of all components are obtained by adding variances. The turbulence components of the LUMM model's dispersion coefficients are conceptually the same as those of the SHORTZ model. The two models differ, however, in the assumed distance dependence of each turbulence component. The lateral and vertical "universal functions" used by the LUMM model were inferred from the equations suggested by Briggs (1973) for rural dispersion coefficients. The Valley, Complex I, Complex II and LUMM models account for the effects of entrainment by the buoyant plume in the same manner except that the LUMM model assumes this contribution to be a factor of 1.4 larger than assumed by the other models. The rationale for this larger contribution is that the radius of the buoyant plume prior to and at the distance of stabilization is 0.6 rather than 0.5 times the plume rise. The SHORTZ and LUMM models account for the effects of vertical wind-direction shear on lateral dispersion in the same manner except that the LUMM model assumes the shear contribution to be 1.5 times larger than assumed by the SHORTZ model and double the contribution originally suggested by Pasquill (1976) which was used in the first version of the LUMM model.

(This Page Intentionally Blank)

SECTION 3

RESULTS OF THE DATA ANALYSES, THE MODEL PERFORMANCE EVALUATION AND THE EMISSION LIMITATION CALCULATIONS

3.1 RESULTS OF THE METEOROLOGICAL AND AIR QUALITY DATA ANALYSES

Figure 1-1 in Section 1.1 shows the locations of Meteorological Tower No. 1, Meteorological Tower No. 2 (the Luke Hill Tower) and the Beryl Meteorological Tower. The hourly meteorological parameters measured at the three towers are summarized in Tables 3-1 through 3-3. Figure 1-1 also shows the locations of the continuous SO_2 monitors operated during the 2-year Westvaco monitoring program. Table 3-4 gives the Universal Transverse Mercator (UTM) X and Y coordinates and elevations of the various meteorological and air quality monitoring sites. For convenience, UTM X and Y coordinates in kilometers are labeled on the sides of Figure 1-1. Table 3-5 gives, for each SO_2 monitor, the distance and azimuth bearing of the Westvaco Main Stack. With the exception of Monitor 10 (Stony Run), all of the monitors were within 1,500 meters of the Main Stack. The azimuth bearings in Table 3-5 also correspond to the wind directions required for the straight-line transport of emissions from the Main Stack to the individual monitors.

The H. E. Cramer Company reviewed and evaluated the concurrent meteorological and SO_2 air quality data from the Westvaco monitoring program as the data were received on a quarterly basis. Our analyses focused on examinations of concurrent meteorological and air quality data for the short-term periods during each quarter with the highest observed ground-level concentrations. These analyses indicated that the observed hourly ground-level concentration patterns often were not consistent with the straight-line transport of the plume from the Westvaco Main Stack to the monitoring network if the wind direction from any level of Tower No. 1 or Tower No. 2 was assumed to be representative of the transport wind direction. Additionally, differences in wind direction between the two towers as large as 180 degrees were not uncommon. The lateral plume dimensions

TABLE 3-1

SUMMARY OF HOURLY METEOROLOGICAL PARAMETERS MEASURED AT TOWER NO. 1

Parameter	Tower Level (m)			
	2	10	50	100
Wind Direction		X	X	X
Wind Speed (Horizontal) $\bar{u}$		X	X	X
Vertical Wind Speed $\bar{w}$		X	X	X
Alongwind Turbulent Intensity I_x		X	X	X
Lateral Turbulent Intensity I_y		X	X	X
Vertical Turbulent Intensity I_z		X	X	X
Ambient Air Temperature T_a		X		
Lower Temperature Difference ΔT_L	X	X		
Upper Temperature Difference ΔT_U		X		X
Net Radiation	-	-	-	-

TABLE 3-2

SUMMARY OF HOURLY METEOROLOGICAL PARAMETERS MEASURED AT TOWER NO. 2

Parameter	Tower Level (m)		
	2	10	30
Wind Direction		X	X
Wind Speed (Horizontal) $\bar{u}$		X	X
Vertical Wind Speed $\bar{w}$		X	X
Alongwind Turbulent Intensity I_x		X	X
Lateral Turbulent Intensity I_y		X	X
Vertical Turbulent Intensity I_z		X	X
Ambient Air Temperature T_a		X	
Lower Temperature Difference ΔT_L	X	X	
Upper Temperature Difference ΔT_U		X	X
Mixing Depth H_m	-	-	-

TABLE 3-3

SUMMARY OF HOURLY METEOROLOGICAL PARAMETERS MEASURED AT THE BERYL TOWER

Parameter	Tower Level (m)	
	10	100
Wind Direction	X	X
Wind Speed (Horizontal) $\bar{u}$	X	X
Vertical Wind Speed $\bar{w}$	X	X
Alongwind Turbulent Intensity I_x	X	X
Lateral Turbulent Intensity I_y	X	X
Vertical Turbulent Intensity I_z	X	X
Ambient Air Temperature T_a	X	
Temperature Difference ΔT	X	X

TABLE 3-4

UNIVERSAL TRANSVERSE MERCATOR (UTM) X AND Y COORDINATES AND ELEVATIONS ABOVE MEAN SEA LEVEL (MSL) OF THE METEOROLOGICAL AND AIR QUALITY MONITORING SITES.

Site	Coordinates		Ground Elevation (m MSL)
	UTM X (m)	UTM Y (m)	
1	667,800	4,370,360	604
2 (Luke Hill)	666,852	4,371,657	468
3	667,638	4,370,259	564
4	667,639	4,370,060	603
5	667,576	4,369,729	639
6	667,860	4,370,604	591
7	667,320	4,369,780	637
8	667,090	4,369,277	643
9	667,412	4,369,278	673
10 (Stony Run)	669,766	4,372,851	504
11 (Bloomington)	665,905	4,371,606	318
Beryl	666,794	4,370,582	307

TABLE 3-5

DISTANCES AND AZIMUTH BEARINGS OF THE WESTVACO MAIN STACK FROM THE SO_2 MONITORS

Site	Distance (m)	Azimuth Bearing (deg)
1	814	299
2 (Luke Hill)	929	165
3	741	312
4	888	322
5	1,111	334
6	784	281
7	1,005	347
8	1,482	360
9	1,515	348
10 (Stony Run)	3,396	231
11 (Bloomington)	1,457	126

inferred from some of the more coherent hourly ground-level concentration patterns were usually much larger than indicated by the lateral turbulent intensity at any level of any tower and appeared to reflect the effects of the wind-direction shear, encountered by the buoyant plume within a transport distance of less than 1 kilometer, as the plume rose from the highly channeled valley flow through a transition layer to the synoptic scale winds above the ridgelines. Because of these unusually large vertical wind-direction shears, the H. E. Cramer Company (January 1981) recommended to EPA Region III that the Cramer, et al. (1972) wind-shear term be added to the SHORTZ model for application at the Westvaco Luke Mill.

We noticed in our examination of the concurrent meteorological and air quality data that the highest short-term concentrations at the monitors south of the Westvaco Main Stack (Monitors 7, 8 and 9 in Figure 1-1) tended to occur during stagnant periods with light winds and large vertical wind-direction shears. In general, the hourly SO_2 concentration patterns were chaotic and did not reflect the presence of a well-defined plume. We hypothesize that these concentrations were caused by one or more of the following factors: (1) curvilinear plume trajectories, (2) plume deformation by wind shear, and (3) previously emitted emissions advected back over the monitors by a wind shift.

Hanna, et al. (1982a, p. 4-31) conclude that the cases of high short-term concentrations at Monitors 7, 8 and 9 occur "during nearly stagnant conditions when the plume slows down and changes direction from up-valley to down-valley or vice versa." According to this explanation, the plume is blown against the valley wall for several hours, especially "if the wind shifts through the north rather than through the south." If this explanation is correct, we would expect very similar hourly concentrations at Monitors 8 and 9 and at Monitors 5 and 7 (see Figure 1-1). Examination of the hourly concentration measurements for the periods with the highest concentrations at these monitors shows that, although the expected similarities in concentrations are found in some cases, there are large differences in concentrations in other cases. Thus, many of the high short-term concentrations south of the Main Stack are not explained by the simple wind-shift hypothesis. Although none of the complex terrain dispersion models described in Section 2 can reproduce the ground-level concentration patterns during the hours with the highest concentrations observed south of the Main Stack, Hanna, et al. (1982a) used qualitative reasoning to create an artificial set of hours with north winds that enabled the LUMM model to match closely the highest 3-hour and 24-hour average SO_2 concentrations paired in space only at Monitors 7, 8 and 9. This set of hours with artificial north winds was deleted in the LUMM model performance evaluation described by Hanna, et al. (1982b) because there was a consensus among the H. E. Cramer Company, EPA Region III, EPA OAQPS and the State of Maryland that the wind-shift hypothesis did not have adequate scientific justification.

All meteorological inputs used in the SHORTZ and LUMM dispersion model performance evaluation were derived from hourly meteorological measurements made at Tower No. 1 and Tower No. 2. It is therefore important to examine the data recovery rates for these towers. The meteorological data recovery rates for the three levels of Tower No. 1 during the first and second years of the monitoring program are listed in Tables 3-6 and 3-7, respectively. Similarly, the meteorological data recovery rates for the two levels of Tower No. 2 as well as for the Luke Hill acoustic sounder during the first and second years are listed in Tables 3-8 and 3-9, respectively. Inspection of Tables 3-6 through 3-9 shows that a data recovery of 90 percent or more generally was attained except for the measurements of the turbulent intensities. As shown at the bottom of Tables 3-6 and 3-8, about half of the turbulence measurements at Tower No. 1 and 35 percent of the turbulence measurements at Tower No. 2 are missing during the first year. Although Tables 3-7 and 3-9 show a considerable improvement in turbulence data recovery rates during the second year of the monitoring program, these rates are generally below 90 percent. It follows that the first year of the Westvaco data set is not well suited for use with any dispersion model which uses turbulence measurements as direct inputs or which uses

TABLE 3-6

DATA RECOVERY RATES AT TOWER NO. 1 DURING THE FIRST YEAR
(SEE TABLE 3-1 FOR DEFINITION OF PARAMETER NOTATION)

Period	Data Recovery Rate (%) for Indicated Parameter at Indicated Tower Level (m)														
	Wind Speed			Wind Direction			I_y			I_z			T_a	ΔT_L	ΔT_U
	10	50	100	10	50	100	10	50	100	10	50	100			
Dec 79	67.5	99.9	99.6	29.6	98.0	69.4	15.5	51.3	38.0	15.1	51.8	38.3	100	100	100
Jan 80	99.1	97.5	99.1	87.6	98.9	52.8	59.8	65.5	36.2	16.5	29.7	34.8	98.5	98.5	95.8
Feb 80	100	100	100	100	100	100	67.4	46.0	66.7	0.0	28.6	46.3	99.7	99.6	99.3
1st Quarter Average	88.9	99.1	99.6	72.4	99.0	74.1	47.6	54.3	47.0	10.5	36.7	39.8	99.4	99.4	98.4
Mar 80	97.7	97.5	97.7	97.7	97.7	97.7	38.2	38.0	38.7	1.8	38.3	26.3	97.7	97.7	97.7
Apr 80	99.3	99.3	99.6	100	100	99.9	68.8	68.3	68.8	61.0	68.2	68.6	99.6	99.6	99.4
May 80	98.4	95.2	98.3	98.4	98.4	98.4	42.6	42.5	43.0	44.4	41.7	43.3	98.3	98.1	98.3
2nd Quarter Average	98.5	97.3	98.5	98.7	98.7	98.7	49.9	49.6	50.2	35.7	49.4	46.1	98.5	98.5	98.5
Jun 80	98.1	98.1	98.1	97.6	98.1	98.1	48.9	48.6	49.9	50.3	49.2	50.3	98.2	98.2	98.2
Jul 80	93.2	98.7	98.7	82.0	96.2	76.6	44.9	55.4	44.0	45.4	51.8	42.9	98.1	96.1	75.9
Aug 80	99.9	99.9	99.9	99.9	99.9	99.9	48.4	48.1	48.5	48.9	48.5	34.8	99.9	99.9	99.9
3rd Quarter Average	97.1	98.9	98.9	93.2	98.1	91.5	47.4	50.7	47.5	48.2	49.8	42.7	98.7	98.1	91.3

TABLE 3-6 (Continued)

Period	Data Recovery Rate (%) for Indicated Parameter at Indicated Tower Level (m)														
	Wind Speed			Wind Direction			I_y			I_z			T_a	ΔT_L	ΔT_U
	10	50	100	10	50	100	10	50	100	10	50	100			
Sep 80	99.3	99.3	99.3	99.3	99.3	99.3	67.1	67.1	66.7	47.2	67.2	18.9	99.3	99.3	99.3
Oct 80	99.9	99.5	100	99.9	100	100	97.5	97.0	97.5	91.5	84.8	88.4	99.5	99.5	99.2
Nov 80	100	93.8	77.5	100	100	77.8	99.3	92.9	75.8	99.0	83.2	75.4	100	100	100
4th Quarter Average	99.7	97.5	92.3	99.7	99.8	92.4	88.0	85.7	80.0	79.2	78.4	60.9	99.6	99.6	99.5
1st Year Average	96.0	98.2	97.3	91.0	98.9	89.2	58.2	60.1	56.2	43.4	53.6	47.4	99.1	98.9	96.9

TABLE 3-7

DATA RECOVERY RATES AT TOWER NO. 1 DURING THE SECOND YEAR
(SEE TABLE 3-1 FOR DEFINITION OF PARAMETER NOTATION)

Period	Data Recovery Rate (%) for Indicated Parameter at Indicated Tower Level (m)														
	Wind Speed			Wind Direction			I_y			I_z			T_a	ΔT_L	ΔT_U
	10	50	100	10	50	100	10	50	100	10	50	100			
Dec 80	97.2	100	99.2	98.9	100	97.3	89.5	89.5	89.3	89.0	88.6	89.1	100	100	100
Jan 81	86.0	99.9	99.9	99.9	99.9	99.9	85.1	98.0	98.1	85.1	78.5	98.0	99.9	99.9	99.2
Feb 81	70.7	100	100	99.4	99.4	100	70.4	98.8	99.9	69.6	36.5	99.6	99.7	99.9	64.3
5th Quarter Average	84.6	100	97.7	99.4	99.8	99.1	81.7	95.4	95.8	81.2	67.9	95.6	99.9	99.9	87.5
Mar 81	99.6	99.6	99.6	99.6	89.1	99.6	97.9	87.5	97.7	97.3	87.5	97.5	99.6	99.6	30.5
Apr 81	100	78.6	88.3	100	71.9	100	99.2	50.1	87.5	99.2	50.6	87.5	100	100	100
May 81	99.5	55.9	98.8	99.3	60.5	99.6	93.0	51.8	92.3	80.4	52.0	57.0	96.9	97.0	96.4
6th Quarter Average	99.7	78.0	95.6	99.6	73.8	99.7	96.7	63.1	92.5	92.3	63.4	80.7	98.8	98.9	75.6
Jun 81	98.6	96.9	98.6	77.8	98.6	98.6	68.5	87.9	88.6	66.3	88.2	89.3	99.0	99.0	98.3
Jul 81	99.5	44.5	99.6	75.5	99.6	99.6	66.0	39.9	89.9	66.0	40.1	89.9	99.6	99.3	99.6
Aug 81	99.3	68.6	98.0	99.9	99.7	100	92.6	62.6	91.4	90.5	60.5	61.3	96.0	94.2	94.1
7th Quarter Average	99.1	70.0	98.7	84.4	99.3	99.4	75.7	63.5	90.0	74.3	62.9	80.2	98.2	97.5	97.3

TABLE 3-8

DATA RECOVERY RATES AT TOWER NO. 2 DURING THE FIRST YEAR
(SEE TABLE 3-2 FOR DEFINITION OF PARAMETER NOTATION)

Period	Data Recovery Rate (%) for Indicated Parameter at Indicated Tower Level (m)											
	Wind Speed		Wind Direction		I_y		I_z		T_a	ΔT_L	ΔT_U	H_m
	10	30	10	30	10	30	10	30				
Dec 79	99.5	100	100	100	57.3	56.9	57.1	57.3	99.2	99.2	99.2	67.6
Jan 80	99.9	45.8	99.9	100	67.5	30.0	65.5	28.9	100	99.2	100	92.5
Feb 80	96.1	84.3	100	100	66.5	56.0	45.6	34.1	100	100	98.6	100
1st Quarter Average	98.5	76.7	100	100	63.8	47.6	56.1	40.1	99.7	99.5	99.3	86.7
Mar 80	71.0	100	100	14.3	34.7	40.6	34.5	40.7	100	100	100	100
Apr 80	99.6	99.2	99.6	88.2	73.2	72.4	71.1	70.7	99.6	99.6	99.6	66.4
May 80	100	100	100	100	46.0	46.1	45.4	45.8	100	100	97.7	99.7
2nd Quarter Average	90.2	99.7	99.9	67.5	51.3	53.0	50.3	52.4	99.9	99.9	99.1	88.7
Jun 80	87.6	88.2	87.6	87.6	47.9	47.2	47.8	47.9	87.5	87.6	91.4	62.5
Jul 80	100	100	100	100	58.6	58.7	59.0	59.1	99.3	99.3	99.3	100
Aug 80	100	100	100	100	81.5	81.3	82.3	81.7	100	100	100	100
3rd Quarter Average	95.9	96.1	95.9	95.9	62.7	62.4	63.0	62.9	95.6	95.6	96.9	87.5

TABLE 3-7 (Continued)

Period	Data Recovery Rate (%) for Indicated Parameter at Indicated Tower Level (m)														
	Wind Speed			Wind Direction			I_y			I_z			T_a	ΔT_L	ΔT_U
	10	50	100	10	50	100	10	50	100	10	50	100			
Sep 81	99.6	99.6	99.6	99.6	99.6	99.6	86.1	86.3	86.4	86.3	86.4	66.4	99.6	89.7	90.4
Oct 81	70.8	98.5	98.7	98.7	83.7	98.7	70.2	83.1	97.9	70.3	83.2	98.0	98.7	98.7	98.7
Nov 81	80.7	95.8	95.7	96.0	78.5	99.6	76.9	74.7	95.1	76.3	73.5	94.7	97.6	97.9	95.0
8th Quarter Average	83.7	98.0	98.0	98.1	87.3	99.3	77.7	81.4	93.1	77.6	81.0	86.4	98.6	95.4	94.7
2nd Year Average	91.8	86.5	98.0	95.4	90.0	99.4	83.0	75.9	92.8	81.4	68.8	85.7	98.9	97.9	88.8
2-Year Average	93.9	92.4	97.7	93.2	94.5	94.3	70.6	68.0	74.5	62.4	61.2	66.5	99.0	98.4	92.9

TABLE 3-8 (Continued)

Period	Data Recovery Rate (%) for Indicated Parameter at Indicated Tower Level (m)											
	Wind Speed		Wind Direction		I_y		I_z		T_a	ΔT_L	ΔT_U	H_m
	10	30	10	30	10	30	10	30				
Sep 80	100	100	100	100	89.4	89.7	86.4	45.4	100	99.7	100	100
Oct 80	99.9	99.9	100	99.9	97.7	97.5	88.6	90.2	99.3	99.3	99.3	83.7
Nov 80	98.3	98.5	100	100	97.6	96.4	78.9	80.1	100	100	100	100
4th Quarter Average	99.4	99.5	100	100	94.9	94.5	84.6	71.9	99.8	99.7	99.8	94.5
1st Year Average	96.0	93.0	98.9	90.8	68.2	64.4	63.5	56.8	98.7	98.7	98.8	89.4

TABLE 3-9

DATA RECOVERY RATES AT TOWER NO. 2 DURING THE SECOND YEAR
(SEE TABLE 3-2 FOR DEFINITION OF PARAMETER NOTATION)

Period	Data Recovery Rate (%) for Indicated Parameter at Indicated Tower Level (m)											
	Wind Speed		Wind Direction		I_y		I_z		T_a	ΔT_L	ΔT_U	H_m
	10	30	10	30	10	30	10	30				
Dec 80	100	99.9	100	100	89.4	89.7	85.2	82.7	100	100	100	100
Jan 81	100	100	100	100	98.4	98.4	98.4	98.4	100	100	100	100
Feb 81	99.7	99.6	100	99.7	96.0	96.1	96.0	96.1	99.4	99.6	99.3	85.6
5th Quarter Average	99.9	99.8	100	99.9	94.6	94.7	93.2	92.4	99.8	99.9	99.8	95.2
Mar 81	100	96.8	100	100	98.3	94.1	97.6	93.2	100	100	100	80.5
Apr 81	99.0	98.9	99.0	98.9	98.3	97.8	97.5	98.1	99.0	99.0	99.0	99.2
May 81	99.9	99.9	99.9	99.9	93.4	93.4	92.7	60.4	99.1	90.7	90.7	90.6
6th Quarter Average	99.6	98.5	99.6	99.6	96.7	95.1	95.9	83.9	99.4	96.6	96.6	90.1
Jun 81	100	100	100	100	98.2	98.2	98.3	62.8	100	100	100	89.4
Jul 81	100	100	100	100	92.6	92.9	33.2	92.9	100	99.3	95.0	97.2
Aug 81	99.9	97.2	99.9	99.9	98.4	95.7	68.8	95.0	96.1	96.2	96.5	75.4
7th Quarter Average	100	99.1	100	100	96.4	95.6	66.8	83.6	98.7	98.5	97.2	87.3

TABLE 3-9 (Continued)

Period	Data Recovery Rate (%) for Indicated Parameter at Indicated Tower Level (m)											
	Wind Speed		Wind Direction		I_y		I_z		T_a	ΔT_L	ΔT_U	H_m
	10	30	10	30	10	30	10	30				
Sep 81	100	100	100	98.9	87.1	86.5	87.2	86.4	100	100	100	81.5
Oct 81	99.9	99.9	20.7	99.9	20.6	99.2	20.6	99.2	99.9	99.9	99.9	99.7
Nov 81	99.7	97.8	81.3	99.2	80.8	96.4	80.8	95.8	99.3	99.3	99.3	100
8th Quarter Average	99.9	99.2	67.3	99.3	62.8	94.0	62.9	93.8	99.7	99.7	99.7	93.7
2nd Year Average	99.8	99.2	91.7	99.7	87.6	94.9	79.7	88.4	99.4	98.7	98.3	91.6
2-Year Average	97.9	96.1	95.3	95.3	77.9	79.6	71.6	72.6	99.1	98.7	98.5	90.5

turbulence measurements to assign the Pasquill stability category to each hour. Consequently, we recommended to EPA Region III that the model performance evaluation be restricted to the second year of the Westvaco monitoring program.

A major deficiency of the Westvaco data set is the absence of valid onsite mixing depths. Minisondes were released from Luke Hill at approximately 0700 and 1330 EST on 21 of the 29 days during February 1980, the third month of the first quarter of the Westvaco monitoring program. We used the minisonde vertical temperature profiles to estimate mixing depths for comparison with the concurrent Luke Hill acoustic sounder mixing depths and with mixing depths estimated from Greater Pittsburgh Airport 0700 and 1900 EST rawinsonde releases. The minisonde and Airport soundings generally revealed the same major synoptic-scale features (for example, a well-defined subsidence inversion). Also, the lower portions of the minisonde temperature profiles closely resembled the temperature profiles constructed from the tower measurements, although the two temperature profiles occasionally showed systematic differences in temperature that are probably attributable to minisonde calibration errors. However, we found no correlation between the onsite tower and minisonde mixing depths and the acoustic sounder mixing depths. We therefore concluded that the acoustic sounder mixing depths are invalid, a conclusion also reached by Hanna, et al. (1982a). In our opinion, the most likely explanation for the invalid acoustic sounder mixing depths is calibration problems. For example, an independent quality assurance audit by Radian Corporation dated 29 January 1982 found that the transmitter's start pulse and operating pulse widths failed to meet manufacturer's specifications.

In the fall of 1977, the H. E. Cramer Company applied the SHORTZ model to the Westvaco Luke Mill using hypothetical meteorological inputs and concluded that, with the current SO_2 emission limitation, emissions from the Main Stack might cause the short-term NAAQS to be slightly exceeded in the vicinity of Monitors 8 and 9. Although the SHORTZ model predicted higher concentrations on elevated terrain closer to the Main Stack, the reliability of these calculated concentrations was not known because they occurred at distances less than the distance at which the buoyant plume typically could be expected to stabilize. When standard "block averages" are used to analyze the hourly SO_2 concentration measurements from the entire 2-year Westvaco monitoring program, Table 3-10 shows 13 observed 3-hour average concentrations above the 3-hour NAAQS and Table 3-11 shows 11 observed 24-hour average concentrations above the 24-hour NAAQS. All of these "block average" 3-hour and 24-hour average concentrations occurred on elevated terrain at distances less than the distances to Monitors 8 and 9. If non-overlapping running mean 3-hour and 24-hour average concentrations are considered for the entire 2-year monitoring program, Tables 3-12 and 3-13 shows that 3-hour and 24-hour average concentrations slightly above the 3-hour and 24-hour NAAQS were measured at Monitors 8 and 9.

3.2 RESULTS OF THE MODEL PERFORMANCE EVALUATION

3.2.1 Results of the Valley Model Performance Evaluation

We used the Valley model, as described in Section 2.2 and Appendix F, to calculate 24-hour average SO_2 concentrations for the nine monitoring sites considered in the dispersion model performance evaluation (see Appendix A for a discussion of the selection of these sites). The emissions data used in the Valley model calculations were for the calendar days during each year of the 2-year Westvaco monitor program with the highest and second-highest observed 24-hour average concentrations at the various monitoring sites. The meteorological conditions assumed in the Valley model calculations were the conditions recommended by Burt and Slater (1977) for screening analyses (F stability and a mean wind speed of 2.5 meters per second). Table 3-14 compares the 24-hour average concentrations calculated for each monitoring site with the observed highest and second-highest 24-hour average concentrations. (The observed 24-hour average concentrations in Table 3-14

TABLE 3-10

BLOCK AVERAGE 3-HOUR AVERAGE SO_2 CONCENTRATIONS ABOVE THE 3-HOUR NATIONAL AMBIENT AIR QUALITY STANDARD

Date	Hours (EST)	Monitor	Concentration ($\mu g/m^3$)
(a) First Year of the Westvaco Monitoring Program			
27 Mar 1980	0400-0600	5	1,472
	0700-0900	5	1,415
31 Jul 1980	0700-0900	4	1,402
13 Nov 1980	1000-1200	6	1,813
(b) Second Year of the Westvaco Monitoring Program			
13 Jan 1981	0400-0600	6	1,389
8 Apr 1981	0400-0600	6	1,386
	0700-0900	6	1,617
22 Oct 1981	0700-0900	1	1,425
13 Nov 1981	0100-0300	7	1,729
	0400-0600	5	1,640
		7	1,955
19 Nov 1981	0700-0900	1	1,376

TABLE 3-11

BLOCK AVERAGE 24-HOUR AVERAGE SO_2 CONCENTRATIONS ABOVE THE 24-HOUR NATIONAL AMBIENT AIR QUALITY STANDARD

Date	Monitor	Concentration (μg/m^3)
(a) First Year of the Westvaco Monitoring Program		
27 Mar 1980	5	435
21 Nov 1980	6	448
(b) Second Year of the Westvaco Monitoring Program		
5 Dec 1980	6	383
29 Dec 1980	1	388
6 Jan 1981	3	427
13 Jan 1981	3	377
	4	406
	6	409
8 Apr 1981	6	401
13 Nov 1981	5	417

TABLE 3-12

NON-OVERLAPPING RUNNING MEAN 3-HOUR AVERAGE SO_2 CONCENTRATIONS ABOVE THE 3-HOUR NATIONAL AMBIENT AIR QUALITY STANDARD

Date	Hours (EST)	Monitor	Concentration ($\mu g/m^3$)
(a) First Year of the Westvaco Monitoring Program			
27 Mar 1980	0400-0600	5	1,472
	0600-0800	8	1,622
		9	1,310
	0700-0900	5	1,417
31 Jul 1980	0700-0900	4	1,402
3-4 Sep 1980	2300-0100	5	1,336
21 Nov 1980	0500-0700	1	1,386
13 Nov 1980	1000-1200	6	1,813
14 Nov 1980	0300-0500	6	1,386
(b) Second Year of the Westvaco Monitoring Program			
13 Jan 1981	0200-0400	1	1,800
		3	1,504
		4	1,517
		6	1,339
8 Apr 1981	0400-0600	6	1,389
	0700-0900	6	1,617
22 Oct 1981	0700-0900	1	1,425
13 Nov 1981	0100-0300	7	1,729
	0400-0600	5	1,640
		7	1,955
		8	1,368
19 Nov 1981	0700-0900	1	1,376
	0900-1100	6	1,527

TABLE 3-13

NON-OVERLAPPING RUNNING MEAN 24-HOUR AVERAGE SO_2 CONCENTRATIONS ABOVE THE 24-HOUR NATIONAL AMBIENT AIR QUALITY STANDARD

Date	Hours (EST)	Monitor	Concentration ($\mu g/m^3$)
(a) First Year of Westvaco Monitoring Program			
26-27 Mar 1980	1000-0900	5	472
13-14 Nov 1980	0800-0700	6	537
20-21 Nov 1980	2200-2100	1	380
		6	500
(b) Second Year of Westvaco Monitoring Program			
5- 6 Dec 1980	0900-0800	6	445
13-14 Dec 1980	2100-2000	6	375
28-29 Dec 1980	1900-1800	1	419
6 Jan 1981	0100-2400	3	427
12-13 Jan 1981	1500-1400	3	367
		4	419
		6	417
	2400-2300	1	474
16-17 Jan 1981	2300-2200	6	372
7- 8 Apr 1981	1800-1700	6	403
30 Apr-1 May 1981	1900-1800	9	390
8- 9 Nov 1981	1300-1200	1	380
12-13 Nov 1981	1200-1100*	7	692
	2000-1900	4	369
		5	424
		6	411
		8	385

* Monitor 7 concentration measurements missing after 1100 EST on 13 November 1981.

TABLE 3-14

COMPARISON OF THE HIGHEST AND SECOND-HIGHEST OBSERVED 24-HOUR AVERAGE SO_2 CONCENTRATIONS WITH THE CONCENTRATIONS CALCULATED BY THE VALLEY MODEL

Monitor	Date	Concentration (ppm)		Ratio of Calculated and Observed Concentrations
		Observed	Calculated	
(a) First-Year (December 1979 through November 1980)				
1	31 Jul 80	0.111	0.762	6.86
	21 Nov 80	0.103	1.280	12.43
3	30 Sep 80	0.079	1.171	14.82
	14 Jun 80	0.073	1.153	15.79
4	31 Jul 80	0.104	0.695	6.68
	25 Jun 80	0.087	0.824	9.47
5	27 Mar 80	0.166	0.676	4.07
	23 Nov 80	0.086	0.682	7.93
6	21 Nov 80	0.171	1.379	8.06
	24 Jun 80	0.124	1.121	9.04
7	23 Nov 80	0.127	0.782	6.16
	20 Nov 80	0.081	0.947	11.69
8	27 Mar 80	0.101	0.485	4.80
	23 Nov 80	0.097	0.491	5.06
9	27 Mar 80	0.103	0.436	4.23
	23 Nov 80	0.084	0.442	5.26
10	28 Jan 80	0.077	0.000	0.00
	2 Jan 80	0.052	0.000	0.00
(b) Second-Year (December 1980 through November 1981)				
1	13 Jan 81	0.180	1.306	7.26
	29 Dec 80	0.148	1.172	7.92
3	6 Jan 81	0.163	1.183	7.26
	13 Jan 81	0.144	1.247	8.66
4	13 Jan 81	0.155	1.193	7.70
	6 Jan 81	0.119	1.146	9.63
5	13 Nov 81	0.159	0.516	3.25
	29 Dec 80	0.112	0.744	6.64
6	13 Jan 81	0.156	1.407	9.02
	8 Apr 81	0.153	1.338	8.75
7	29 Dec 80	0.110	0.853	7.75
	22 Apr 81	0.101	0.772	7.64
8	13 Nov 81	0.130	0.369	2.84
	9 Jan 81	0.091	0.577	6.34
9	1 May 81	0.112	0.446	3.98
	13 Nov 81	0.111	0.331	2.98
10	9 Jan 81	0.091	0.000	0.00
	3 Jan 81	0.048	0.000	0.00

have not been adjusted for the effects of "background," which we define in this report as ambient SO_2 concentrations attributable to emissions from sources other than the Westvaco Main Stack.) The ratio of calculated to observed concentrations ranges from 2.98 to 15.79 for all monitors except Monitor 10. Under the assumed "worst-case" meteorological conditions, the Westvaco plume does not mix far enough downward in the Valley model calculations to cause a non-zero concentration at Monitor 10. In a regulatory application of the Valley model, all elevated terrain at and beyond the boundaries of the Westvaco property would be considered in the model analysis. Monitors 8 and 9 are on elevated terrain near the southern boundary of the Westvaco property, and the bias toward overestimation at these monitors tends to support the continued use of the Valley model as a safe-sided screening model.

3.2.2 Results of the Complex I and II Model Performance Evaluation

As discussed in Section 2 and Appendix F, the Valley and Complex I models are based on very similar assumptions. If the wind is contained within a 22.5-degree sector for 6 hours of a 24-hour period and the meteorological conditions during these 6 hours consist of F stability and an average wind speed of 2.5 meters per second, the 24-hour average concentrations calculated by the two models at receptors in the downwind 22.5-degree sector are equivalent. Because of the conservativeness of the Valley model for the Westvaco data set, it follows that the Complex I model should also be a safe-sided screening model for the Westvaco data set. The Complex II model predicts higher hourly concentrations than the Complex I model because the crosswind concentration distribution is assumed to be Gaussian (as described by Pasquill-Gifford lateral dispersion coefficients) rather than uniform within a 22.5-degree sector. Consequently, the Complex II model should also be a safe-sided screening model for the Westvaco data set. Of the five complex terrain dispersion models described in Section 2, only the generalized SHORTZ model and the site-specific LUMM model were considered to be likely candidates as refined (non-screening) models for the Westvaco data set. It was therefore the joint decision of the H. E. Cramer Company and the EPA Project Officer that the detailed model performance evaluation should be restricted to the SHORTZ and LUMM models.

3.2.3 Results of the SHORTZ and LUMM Model Performance Evaluation

On 21 October 1982, Westvaco Corporation, the State of Maryland, EPA Region III and EPA OAQPS agreed to a protocol for the selection of the SHORTZ model or the LUMM model as the complex terrain dispersion model to be used to establish an SO_2 emission limitation for the Main Stack at the Westvaco Luke Mill. A copy of this model performance evaluation is contained in Appendix A. As discussed in the 21 October 1982 protocol, the model evaluation was restricted to the second year of the Westvaco monitoring program because of the large fraction of missing turbulence measurements (key meteorological inputs to both the SHORTZ and LUMM models) during the first year of the monitoring program. Westvaco, the State of Maryland and EPA also agreed on 21 October 1982 that the performance evaluation for the SHORTZ and LUMM models would be conducted by ERT and reviewed by the H. E. Cramer Company. The results of the model performance evaluation have been summarized by Hanna, et al (1982b) and verified by Bowers and Hargraves (1982). The remainder of this subsection is primarily based on the report by Bowers and Hargraves (1982).

Observed (Minus Background) SO_2 Concentrations

We used the observed hourly SO_2 concentrations provided to EPA Region III by ERT for the second year of the Westvaco monitoring program to determine, for each monitor of concern for the model performance evaluation (Monitors 1', 3, 4, 5, 6, 7, 8, 9 and 10), the 25 highest 1-hour, 3-hour and 24-hour average and the annual average observed (minus background) SO_2

concentrations. The procedures used to adjust the hourly concentrations for background (defined as ambient SO_2 concentrations attributable to emissions from sources other than the Westvaco Main Stack) and to account for hours with missing concentration measurements are outlined in the 21 October 1982 model evaluation protocol contained in Appendix A. The results of our analysis of the observed hourly SO_2 concentrations are presented in Appendix B.

Table 3-15 compares the highest and second-highest observed (minus background) 3-hour and 24-hour average SO_2 concentrations calculated at each monitor of concern by ERT and the H. E. Cramer Company. To facilitate comparison of the two sets of observed (minus background) SO_2 concentrations, we divided the concentrations reported by Hanna, et al. (1982b) in units of micrograms per cubic meter by 2,620 to obtain concentrations in units of parts per million (ppm), the units used to archive the observed hourly SO_2 concentrations. The two sets of 3-hour average concentrations in Table 3-15 agree identically and the 24-hour average concentrations agree to within about 1 percent. However, not all of the observed (minus background) concentrations calculated by ERT and the H. E. Cramer Company show such close agreement. For example, Table 3-16 shows differences of up to 8 percent in some of the 25 highest 24-hour average concentrations. We manually verified our observed (minus background) 24-hour average concentrations in Table 3-16 using the observed hourly SO_2 concentrations provided to EPA Region III by ERT. We subsequently learned that the differences in the observed (minus background) concentrations independently calculated by ERT and the H. E. Cramer Company are attributable to slightly different interpretations of the background estimation procedures outlined in the 21 October 1982 model evaluation protocol.

In our determination of the observed (minus background) hourly SO_2 concentrations for the Westvaco model evaluation study, we defined the background during each hour as the lowest observed hourly SO_2

Table 3-15

COMPARISON OF THE HIGHEST AND SECOND-HIGHEST OBSERVED (MINUS BACKGROUND) 3-HOUR AND 24-HOUR AVERAGE SO_2 CONCENTRATIONS CALCULATED BY ERT AND THE H. E. CRAMER COMPANY

Monitor	3-Hour Concentrations (ppm)		24-Hour Concentrations (ppm)		Ratio of ERT and HEC Concentrations	
	ERT	HEC	ERT	HEC	3-Hour Concentrations	24-Hour Concentrations
(a) Highest Concentrations						
1	0.5412	0.5412	0.1666	0.1666	1.000	1.000
3	0.4337	0.4337	0.1585	0.1585	1.000	1.000
4	0.4560	0.4560	0.1411	0.1419	1.000	0.994
5	0.6235	0.6235	0.1540	0.1546	1.000	0.996
6	0.6142	0.6142	0.1487	0.1501	1.000	0.991
7	0.7432	0.7432	0.0991	0.0994	1.000	0.997
8	0.5195	0.5195	0.1247	0.1255	1.000	0.994
9	0.4728	0.4728	0.1088	0.1099	1.000	0.990
10	0.1592	0.1592	0.0433	0.0433	1.000	1.000
(b) Second-Highest Concentrations						
1	0.5158	0.5158	0.1374	0.1375	1.000	0.999
3	0.3842	0.3842	0.1309	0.1309	1.000	1.000
4	0.3733	0.3733	0.1142	0.1147	1.000	0.996
5	0.4518	0.4518	0.1011	0.1015	1.000	0.996
6	0.5268	0.5268	0.1432	0.1432	1.000	1.000
7	0.6575	0.6575	0.0946	0.0947	1.000	0.999
8	0.3325	0.3325	0.0808	0.0820	1.000	0.985
9	0.4008	0.4008	0.1061	0.1070	1.000	0.992
10	0.1120	0.1120	0.0373	0.0373	1.000	1.000

TABLE 3-16

COMPARISON OF SELECTED OBSERVED (MINUS BACKGROUND) 24-HOUR AVERAGE CONCENTRATIONS CALCULATED BY ERT AND THE H. E. CRAMER COMPANY AT MONITOR 10

Date	24-Hour Concentrations (ppm)		Ratio of ERT and HEC Concentrations
	ERT	HEC	
5 Jul 81	0.0190	0.0206	0.922
6 Oct 81	0.0160	0.0173	0.925

concentration if this concentration was above the monitor threshold concentration of 0.005 parts per million (13 micrograms per cubic meter). If the lowest observed concentration was equal to 0.005 parts per million (ppm), we arbitrarily defined the background concentration as 0.0025 ppm (6.5 micrograms per cubic meter). We then subtracted the background concentration estimated for each hour from all of the observed concentrations. Thus, our minimum observed (minus background) hourly concentration was 0.0025 ppm. According to Memo No. PSC-1537 (30 November 1982, "Determination of Observed Concentrations Used in Model Performance Evaluation at the Luke Mill"), ERT followed essentially the same approach. However, if the lowest observed hourly concentration was 0.005 ppm during an hour, ERT defined the observed (minus background) concentrations as zero at all monitors with observed concentrations of 0.005 ppm and the observed (minus background) concentrations as the observed concentrations minus 0.0025 ppm at all monitors with concentrations above 0.005 ppm. The differences in the observed (minus background) 24-hour average SO_2 concentrations independently calculated by ERT and the H. E. Cramer Company are explained by ERT's use of several zero observed (minus background) hourly concentrations.

Table 3-17 lists the observed (minus background) annual average SO_2 concentrations calculated for the second year of the Westvaco monitoring program by ERT and the H. E. Cramer Company. There is an exact agreement between the two observed (minus background) annual average SO_2 concentrations calculated for Monitor 3. However, the remainder of the observed (minus background) annual average concentrations calculated by ERT are lower than the corresponding concentrations calculated by the H. E. Cramer Company, with a maximum difference of 25 percent at Monitor 10. We believe that the differences in the procedures used by ERT and the H. E. Cramer Company to adjust the observed hourly concentrations for background probably explain the differences in the two sets of observed (minus background) annual average concentrations.

TABLE 3-17

COMPARISON OF THE OBSERVED (MINUS BACKGROUND) ANNUAL AVERAGE SO_2 CONCENTRATIONS CALCULATED BY ERT AND THE H. E. CRAMER COMPANY

Monitor	Annual Concentrations (ppm)		Ratio of ERT and HEC Concentrations
	ERT	HEC	
1	0.021	0.022	0.955
3	0.018	0.018	1.000
4	0.013	0.014	0.929
5	0.012	0.014	0.857
6	0.033	0.034	0.971
7	0.012	0.014	0.857
8	0.011	0.012	0.917
9	0.010	0.011	0.909
10	0.006	0.008	0.750

The model evaluation protocol in Appendix A specified that a 3-hour period must include 3 valid concentration measurements to be considered in the set of the 25 highest 3-hour average concentrations for a monitor. Our examination of the tables of 25 highest observed (minus background) 3-hour average concentrations listed in Appendix A of the Hanna, et al. (1982b) report indicates that ERT did not follow this procedure. If a 3-hour period contained 2 hours of valid concentration measurements, ERT defined the "3-hour average" concentration for the period by the 2-hour average concentration for the two hours with valid concentration measurements. The affected monitors are:

- Monitor 5 during the third 3-hour period on 20 May 1981
- Monitors 7, 8 and 9 during the second 3-hour period on 18 October 1982

The differences in the 25 highest observed (minus background) 3-hour average SO_2 concentrations calculated by ERT and the H. E. Cramer Company for Monitors 5, 7, 8 and 9 are not sufficient to affect the outcome of the model performance evaluation.

The model evaluation protocol contained in Appendix A states that standard "block average" observed (minus background) and calculated 3-hour and 24-hour average concentrations shall be compared. A 3-hour period must contain 3 hours of valid concentration measurements to be considered in the comparison, while a 24-hour period must contain 18 hours of valid data. These criteria can have significant effects on the results of the model performance evaluation. For example, the highest observed (minus background) 24-hour average SO_2 concentrations calculated for Monitor 7 under these criteria is 0.0994 ppm on 29 December 1980. The highest and second-highest observed (minus background) 3-hour average SO_2 concentrations at Monitor 7 both occurred on 13 November 1981, a day not considered in the 24-hour block averages because of missing observations after 1100 EST on 13 November. If the concentration at Monitor 7 is defined as zero during the period 1200 through 2400 EST on 13 November, the resulting observed (minus background) 24-hour average concentration is 0.1971 ppm, which is 1.98 times the observed (minus background) concentration on 29 December 1980. For the period 1200 EST on 12 November through 1100 EST on 13 November, the observed (minus background) 24-hour average concentration at Monitor 7 is 0.2599 ppm, which is 2.61 times the observed (minus background) concentration on 29 December 1980.

SHORTZ Model Calculations

To assist ERT in the LUMM and SHORTZ dispersion model evaluation, the H. E. Cramer Company provided ERT with a computer tape containing: (1) the SHORTZ hourly meteorological and source inputs developed for the second year of the Westvaco monitoring program following the procedures specified in the model evaluation protocol (see Appendix A), and (2) the computer code for the SHORTZ model as described in the model evaluation protocol. Additionally, the H. E. Cramer Company provided ERT with specific guidance on how SHORTZ should be executed (see Table 9 of the protocol). Appendix C of this report contains tables which list the 25 highest 1-hour, 3-hour and 24-hour average and the annual average SO_2 concentrations calculated at each monitor of concern for the model evaluation by the H. E. Cramer Company using the SHORTZ model. The cumulative frequency distributions of these sets of 25 highest calculated short-term SO_2 concentrations are compared with the cumulative frequency distributions of the corresponding observed (minus background) short-term concentrations in Appendix D.

Table 3-18 compares the highest and second-highest 3-hour and 24-hour average SO_2 concentrations calculated at each monitor of concern by ERT and the H. E. Cramer Company using the SHORTZ model. Because the two sets of calculated short-term concentrations agree to within less than plus or minus 1 percent, we conclude that the differences in the two sets of calculated concentrations are attributable to differences in the accuracy of the computer systems used by ERT and the H. E. Cramer Company. On the

Table 3-18

COMPARISON OF THE HIGHEST AND SECOND-HIGHEST 3-HOUR AND 24-HOUR AVERAGE SO_2 CONCENTRATIONS CALCULATED BY ERT AND THE H. E. CRAMER COMPANY USING THE SHORTZ MODEL

Monitor	3-Hour Concentrations (ppm)		24-Hour Concentrations (ppm)		Ratio of ERT and HEC Concentrations	
	ERT	HEC	ERT	HEC	3-Hour Concentrations	24-Hour Concentrations
(a) Highest Concentrations						
1	3.1680	3.1736	0.7143	0.7163	0.998	0.997
3	4.1082	4.1034	0.8524	0.8503	1.001	1.002
4	2.4836	2.4823	0.4259	0.4258	1.001	1.000
5	1.1894	1.1889	0.2866	0.2866	1.000	1.000
6	3.1451	3.1442	0.8228	0.8225	1.000	1.000
7	1.2502	1.2483	0.2334	0.2330	1.002	1.002
8	0.6525	0.6529	0.0920	0.0922	0.999	0.998
9	0.7586	0.7543	0.1026	0.1029	1.006	0.997
10	0.1586	0.1591	0.0457	0.0458	0.997	0.998
(b) Second-Highest Concentrations						
1	3.1459	3.1540	0.6689	0.6694	0.997	0.999
3	2.5391	2.5276	0.6674	0.6660	1.005	1.002
4	2.1491	2.1496	0.4051	0.4050	1.000	1.000
5	1.0550	1.0557	0.2095	0.2096	0.999	1.000
6	2.9054	2.9067	0.7709	0.7722	1.000	0.998
7	0.9574	0.9606	0.1612	0.1610	0.997	1.001
8	0.5834	0.5838	0.0820	0.0821	0.999	0.999
9	0.5566	0.5581	0.0979	0.0974	0.997	1.005
10	0.1335	0.1338	0.0413	0.0414	0.998	0.998

other hand, Table 3-19 shows differences in the annual average SO_2 concentrations calculated by ERT and the H. E. Cramer Company that are more difficult to explain by differences in machine accuracy. However, we point out that the differences in the two sets of calculated annual average concentrations in Table 3-19 are not sufficient to affect the outcome of the model performance evaluation.

As noted above, ERT included in the determination of the sets of 25 highest observed (minus background) 3-hour average SO_2 concentrations several 2-hour average concentrations for 3-hour periods with only 2 valid hourly concentration measurements. This same procedure, which deviates from the model evaluation protocol contained in Appendix A, was also followed in processing the results of the hourly concentrations calculated by ERT using the SHORTZ model. The SHORTZ hourly meteorological inputs contain a total of 18 hours flagged as missing because of calm or variable winds at all levels of Tower No. 1 and Tower No. 2 (see the second footnote at the bottom of Table 2 in the model evaluation protocol). The inclusion by ERT of 3-hour periods containing a single hour with missing calculated concentrations affects the following monitors:

- Monitor 6 during the eighth 3-hour period on 5 May 1981
- Monitors 8 and 9 during the first 3-hour period on 30 September 1981

The differences in the 25 highest 3-hour average concentrations calculated by ERT and the H. E. Cramer Company for Monitors 6, 8 and 9 using the SHORTZ model are not sufficient to affect the outcome of the model performance evaluation.

Performance Statistics and Scores

As explained in the model evaluation protocol contained in Appendix A, the following parameters were used to compute the scores for the LUMM

TABLE 3-19

COMPARISON OF THE ANNUAL AVERAGE SO_2 CONCENTRATIONS CALCULATED BY ERT AND THE H. E. CRAMER COMPANY USING THE SHORTZ MODEL

Monitor	Annual Concentrations (ppm)		Ratio of ERT and HEC Concentrations
	ERT	HEC	
1	0.0874	0.0905	0.966
3	0.0462	0.0422	1.095
4	0.0271	0.0279	0.971
5	0.0115	0.0116	0.991
6	0.1603	0.1573	1.019
7	0.0099	0.0092	1.076
8	0.0034	0.0037	0.919
9	0.0050	0.0048	1.042
10	0.0046	0.0045	1.022

and SHORTZ models: (1) the ratio of the absolute value of the bias (residual) for the model being evaluated to the absolute value of the minimum bias (residual) for either of the two models, (2) the minimum of the ratio of calculated and observed concentrations and the ratio of observed and calculated concentrations, and (3) the minimum of the ratio of the variances of the calculated and observed concentrations and the ratio of the variances of the observed and calculated concentrations. We used the results of our analysis of the observed hourly SO_2 concentrations (see Appendix B) and our analysis of the hourly SO_2 concentrations calculated by SHORTZ (see Appendix C) to compute biases (residuals) and variances for comparison with the corresponding values computed by ERT. The agreement between the two sets of performance statistics was consistent with the agreement between the two independent analyses of the observed concentrations and the two sets of SHORTZ model predictions discussed above. We also used the observed (minus background) concentrations and the concentrations calculated by the LUMM model that are given in Appendix A of the Hanna, et al. (1982b) report to compute and verify the biases (residuals) and variances listed for the LUMM model in Table 17 of the Hanna, et al. (1982b) report. Finally, we checked the protocol scoring results shown in Table 17. If the concentrations, biases (residuals) and variances given in Table 17 are accepted as accurate, we disagree with ERT's scoring only for the comparison of the 25 highest observed (minus background) 24-hour average concentrations at Monitor 10 paired in space with the 25 highest 24-hour average concentrations calculated by the LUMM model. From Equation (9) of the model evaluation protocol and for the concentrations and biases in Table 17, the score for LUMM is

$$\begin{aligned}\{\text{Score Model}_i\} &= \frac{|\Delta\chi|\text{min}}{|\Delta\chi_i|} \times \text{MIN}\{C_i/O, O/C_i\} \times \{\text{Possible Points}\} \\ &= \frac{4}{17} \times \frac{45}{62} \times (20) = 3.4 \qquad (3\text{-}1) \\ &= 3 \text{ to the nearest integer}\end{aligned}$$

The score in Table 17 is given as 4 rather than 3.

Table 3-20 summarizes the qualitative performance of the LUMM and SHORTZ models by monitor. The LUMM model has the highest score at six monitors (Monitors 1, 3, 4, 5, 6 and 7) and the SHORTZ model has the highest score at three monitors (Monitors 8, 9 and 10). Table 3-20 does not indicate any clear trend in model performance according to monitor elevation above the top of the Westvaco Main Stack. For example, the SHORTZ model has the highest score at both the monitor with the highest elevation and the monitor with the lowest elevation. On the other hand, Table 3-20 appears to indicate a trend in model performance according to distance from the Main Stack. The LUMM model has the highest score at each monitor less than or equal to 1.1 kilometers from the Main Stack and the SHORTZ model has the highest score at each monitor greater than or equal to 1.5 kilometers from the Main Stack.

The scores given in Table 17 of the Hanna, et al. (1982b) report for the LUMM and SHORTZ models are 363 and 168, respectively. Under the assumption that all of the concentrations, biases (residuals) and variances in Table 17 are correct, we believe that the score for the LUMM model should actually be 362 for the reason given above. Also, as discussed above, there are some differences in ERT's and the H. E. Cramer Company's analyses of the observed hourly SO_2 concentrations and of the hourly SO_2 concentrations calculated by the SHORTZ model. However, these differences are relatively small and do not affect the total score for either model by more than a few points because the score for each comparison is rounded to the nearest integer. We conclude that we are in agreement with ERT that the LUMM model has the highest score.

Summary and Conclusion of the Model Performance Evaluation

Westvaco Corporation, the State of Maryland and EPA agreed on 21 October 1982 to a protocol for the evaluation of the performance of the LUMM and SHORTZ complex terrain dispersion models using the Westvaco data set. According to this protocol, the model to be used to establish an

TABLE 3-20

SUMMARY OF MODEL PERFORMANCE BY MONITORING SITE

Monitor	Distance from Main Stack (km)	Elevation Above Main Stack Top (m)	Model with Highest Score
1	0.8	126	LUMM
3	0.7	86	LUMM
4	0.9	125	LUMM
5	1.1	161	LUMM
6	0.8	113	LUMM
7	1.0	159	LUMM
8	1.5	165	SHORTZ
9	1.5	195	SHORTZ
10	3.4	26	SHORTZ

SO_2 emission limitation for the Main Stack at the Westvaco Luke, Maryland Mill is the model with the highest score. Westvaco's consultant (ERT) conducted the model performance evaluation and concluded that the scores for the LUMM and SHORTZ models are 363 and 168, respectively. Under contract to EPA, the H. E. Cramer Company independently verified all of the results of the ERT model performance evaluation except the predictions of the LUMM model. We identified one minor deviation by ERT from the 21 October 1982 protocol and what we believe to be a single-point scoring error. Also, there are several minor differences in the analyses of the observed and calculated (SHORTZ) hourly SO_2 concentrations independently performed by ERT and the H. E. Cramer Company. However, the deviation by ERT from the protocol and the differences in the independent analyses of observed and calculated (SHORTZ) hourly concentrations do not change the score for either model by more than a few points. Under the terms of the protocol, we therefore conclude that the LUMM model is the model to be used to establish an SO_2 emission limitation for the Westvaco Main Stack.

3.3 RESULTS OF THE SO_2 EMISSION LIMITATION CALCULATIONS

The site specific LUMM model was identified as the complex terrain dispersion model to be used to establish an SO_2 emission limitation for the Main Stack at the Westvaco Luke Mill under the terms of the 21 October 1982 model evaluation protocol contained in Appendix A. Under the assumption that the only constraint on the SO_2 emission limitation for the Westvaco Main Stack is that emissions do not endanger the NAAQS for SO_2, ERT (December 1982) used the LUMM model to estimate an emission limitation of 75.1 tons per day (3-hour average concentration for 50 percent buoyancy flux). Under this assumption and assuming that the LUMM model calculations were performed correctly, we agree with the ERT (December 1982) computation of an emission limitation.

In the absence of the data from the 2-year Westvaco monitoring program and the model performance evaluation, the SO_2 emission limitation for the Westvaco Main Stack would probably be determined by EPA on the basis of predictions made using the Complex I model with any available onsite meteorological data. To gain insight to the differences in emission limitations arising from the two different modeling approaches, we used the Complex I model with the source and meteorological inputs developed for the second year of the Westvaco monitoring program (see Table 1 in Appendix A) to estimate an emission limitation. As discussed in Section 2, we modified the Complex I model's computer code to read hourly values of the stack exit temperature, the stack exit velocity and the vertical potential temperature gradient and to key the selection of the stable or adiabatic plume rise equation on the vertical potential temperature gradient.

The Complex I model requires an estimate of the Pasquill stability category during each hour in order to assign the appropriate wind-profile exponent and Pasquill-Gifford vertical dispersion coefficient. The October 1980 draft EPA report "Proposed Revisions to the Guideline on Air Quality Models" suggests that the hourly vertical turbulent intensity (standard deviation of the wind elevation angle in radians) measured 10 meters above ground-level can be used to assign the appropriate stability category. Table 3-21, which is based on Table C-1 of the October 1980 draft EPA report, shows the suggested ranges of vertical turbulent intensities corresponding to the various stability categories for a surface roughness length z_o of 15 centimeters. The draft EPA report suggests that these ranges be adjusted to the roughness length of the site using a $z_o^{0.2}$ law. According to the wind-tunnel and field studies of the Westvaco Mill described by Weil (1979) and Weil, _et al_. (1981), the roughness length in the vicinity of the Westvaco Mill is about 16 meters. Table 3-22 gives the adjusted ranges of vertical turbulent intensities for a 16-meter roughness length. Because the A, B and C stability categories almost never occur in the Westvaco data set with the stability classification scheme shown in Table 3-22, we used the scheme shown in Table 3-21 after consultation with the EPA Project Officer. Our first and second choices of hourly vertical turbulent intensities for use with Table 3-21 were the values measured at the 10-meter levels of Tower No. 2 and Tower No. 1, respectively. If both of the 10-meter

TABLE 3-21

STABILITY CLASSIFICATION SCHEME SUGGESTED BY EPA FOR A SURFACE ROUGHNESS LENGTH OF 15 CENTIMETERS

Pasquill Stability Category	10m Vertical Turbulent Intensity (rad)
A	>0.2094
B	0.1746 to 0.2094
C	0.1362 to 0.1745
D	0.0874 to 0.1361
E	0.0419 to 0.0873
F	<0.0419

TABLE 3-22

PROPOSED EPA STABILITY CLASSIFICATION SCHEME FOR A SURFACE ROUGHNESS LENGTH OF 16 METERS

Pasquill Stability Category	10m Vertical Turbulent Intensity (rad)
A	>0.5329
B	0.4441 - 0.5329
C	0.3464 - 0.4440
D	0.2221 - 0.3463
E	0.1066 - 0.2220
F	<0.1066

observations were missing, we selected from the available measurements the vertical turbulent intensity from the next lowest level of Tower No. 2 or Tower No. 1.

We used the actual hourly values of the stack exit velocity and stack exit temperature in the Complex I model calculations to estimate an SO_2 emission limitation for the Westvaco Main Stack. However, we assumed a constant SO_2 emission rate of 1,000 grams per second for convenience. We used discrete receptors to form a polar receptor array centered on the Main Stack with a 10-degree angular spacing between radials. Excluding the Westvaco property shown in Figure 7-1 of the Hanna, et al. (1982a) report, we placed receptors at 500-meter intervals along each radial to the highest terrain feature between 2.5 and 5.0 kilometers from the stack. The receptors on each radial extended a minimum of 2 kilometers beyond the Westvaco property boundary. Additional receptors were placed on the prominent high terrain features that were not adequately covered by the polar receptor array. Because the Complex I model's computer code accepts a maximum of only 180 receptors, it was necessary to perform two computer runs to include all of the 262 receptors.

Table 3-23 gives the maximum annual and highest of the second-highest 3-hour and 24-hour average SO_2 concentrations calculated by the Complex I model for emissions from the Westvaco Main Stack assuming an emission rate of 1,000 grams per second. All of the calculated concentrations in Table 3-23 are located at a point 4.5 kilometers west-northwest of the Main Stack that is about 110 meters above the stack-top elevation. The meteorological conditions during the first 3 hours of 1981 Julian Day 45 consisted of light east-southeast winds (wind speeds less than 1.0 meter per second, defined as 1.0 meter per second for use in the model calculations) in combination with 2 hours of F stability and a single hour of D stability. The meteorological conditions on 1981 Julian Day 287 consisted of light-to-moderate winds (wind speeds from 1.0 to 4.5 meters per second) within the sector 085 to 115 degrees in combination with 16 hours of E stability, 6 hours of D stability and a single hour each of A stability and F stability.

TABLE 3-23

MAXIMUM ANNUAL AND HIGHEST OF THE SECOND-HIGHEST 3-HOUR AND 24-HOUR AVERAGE SO_2 CONCENTRATIONS CALCULATED BY THE COMPLEX I MODEL FOR EMISSIONS FROM THE WESTVACO MAIN STACK ASSUMING AN EMISSION RATE OF 1,000 GRAMS PER SECOND

Averaging Time	Year/Julian Day (Period)	Location*		Elevation (m MSL)	Concentration ($\mu g/m^3$)
		Distance (m)	Azimuth Bearing (deg)		
3 Hour	1981/45(1)	4,500	290	588	2,543
24 Hour	1981/287	4,500	290	588	1,123
Annual	--	4,500	290	588	92.7

*Locations are with respect to the Westvaco Main Stack.

Both the 3-hour and 24-hour periods were characterized by large hourly vertical wind-direction shears and/or hourly lateral turbulent intensities. Consequently, the "worst-case" short-term periods for the Complex I model are relatively high dilution periods for the SHORTZ and LUMM models.

We computed an SO_2 emission limitation for the Westvaco Main Stack under the following assumptions: (1) the NAAQS for SO_2 are the only constraints, and (2) the background SO_2 concentration is 13 micrograms per cubic meter for all concentration averaging times. Under these assumptions, the allowable SO_2 emission rate is given by

$$Q_{SO_2}(\mathrm{g/sec}) = \frac{1000(\mathrm{NAAQS}-13)}{\chi_c(\mu\mathrm{g/m}^3)} \qquad (3\text{-}2)$$

where χ_c is the calculated concentration from Table 3-23 and 1,000 is the SO_2 emission rate used in the Complex I model calculations. The resulting allowable emission rate is given in Table 3-24 for each NAAQS. As shown by the table, the 24-hour NAAQS restricts the allowable SO_2 emissions to about 29.9 tons per day in the Complex I model calculations, a factor of 2.5 lower than the emission limitation of 75.1 tons per day determined by ERT (December 1982) using the LUMM model.

TABLE 3-24

MAXIMUM ALLOWABLE SO_2 EMISSION RATES FOR THE WESTVACO MAIN STACK BASED ON THE RESULTS OF THE COMPLEX I CALCULATIONS

Averaging Time	Allowable SO_2 Emission Rate*	
	(g/sec)	(ton/day)
3 Hours	506.1	48.2
24 Hours	313.4	29.9
Annual	722.8	68.8

* The allowable SO_2 emission rates assume: (1) the background SO_2 concentration is 13 micrograms per cubic meter for all concentration averaging times, and (2) compliance with the National Ambient Air Quality Standards (NAAQS) is the only constraint on Westvaco SO_2 emissions.

(This Page Intentionally Blank)

SECTION 4

CONCLUSIONS

In our opinion, the Westvaco data set is the most detailed and best documented data set developed to date for the purpose of evaluating and validating complex terrain dispersion models. However, we believe that the Westvaco Luke Mill modeling problem is sufficiently unique that any conclusions about the accuracy of dispersion models evaluated using the Westvaco data set should be used with caution unless they are supported by previous (and/or future) experience in testing the models in complex terrain. Also, the Westvaco data set contains ambiguities that are unlikely ever to be resolved. For example, we question whether the sequence of events and the physical processes leading to the occurrence of the highest short-term SO_2 concentrations at the monitors on elevated terrain south of the Westvaco Main Stack (Monitors 7, 8 and 9 in Figure 1-1) can ever be determined with any acceptable degree of confidence using the archived hourly average data. With these caveats, the following paragraphs discuss our conclusions about: (1) complex terrain dispersion model performance, (2) meteorological measurements to develop dispersion model inputs in areas of complex terrain, and (3) the effects of monitoring network design on the results of dispersion model performance evaluations.

Dispersion Model Performance

The complex terrain dispersion models considered in the Westvaco model evaluation study can be divided into two general categories: (1) screening models (the Valley, Complex I and Complex II models), and (2) refined models (the SHORTZ and LUMM models). The objective of the screening models is to provide safe-sided estimates of maximum short-term concentrations when little or no onsite meteorological data are available. Because this objective generally was satisfied by the three screening models, we believe that they can be defined as state-of-the-art complex terrain screening models. The objective of the refined models is to use onsite meteorological measurements to provide accurate and unbiased estimates of the highest short-term concentrations. This objective was satisfied by the LUMM model at all monitors located between 0.7 and 1.1 kilometers from the Westvaco Main Stack and by the SHORTZ model at all monitors located between 1.5 and 3.4 kilometers from the Main Stack. The performance of the LUMM and SHORTZ models for the Westvaco data set appears to be a function only of distance from the Main Stack; the SHORTZ model has the best quantitative performance at the monitors with both the lowest and highest elevations above the stack-top elevation. Assuming that the typical distance to plume stabilization is on the order of ten stack heights (Briggs, 1969), one possible interpretation of the results of the performance evaluation is that the LUMM model is the state-of-the-art refined model at distances less than the distance to plume stabilization and the SHORTZ model is the state-of-the-art refined model at longer downwind distances. We conclude from these results that both the LUMM and SHORTZ models are state-of-the-art refined models for the Westvaco data set. However, under the terms of the 21 October 1982 model evaluation protocol, we also conclude that the LUMM model should be used to establish an SO_2 emission limitation for the Westvaco Main Stack.

The LUMM model was specifically developed for application to the Westvaco data set, and the final version of the model represents the combination of model constants and meteorological inputs that yields the best fit to the air quality measurements. Consequently, the LUMM model cannot be assumed to be a generalized state-of-the-art complex terrain dispersion model. However, many of the concepts upon which the LUMM model is based may be suitable for generalized applications, and we believe that it would be desirable to conduct additional performance evaluations of these concepts. The SHORTZ model, on the other hand, has been applied as a generalized complex terrain dispersion model over a period of almost 8 years. Although previous tests of the SHORTZ model (see Appendix H of Bjorklund and Bowers, 1982) have not been as rigorous as the Westvaco model performance evaluation, the results of these tests have consistently shown a close agreement between calculated and observed short-term SO_2 concentrations for sources located in complex terrain. The Westvaco data set offered the first opportunity to date to utilize the SHORTZ model's capability of directly relating turbulence measurements to plume expansion. After modification of the SHORTZ model to account for the large vertical wind-direction shears (sometimes as large as 180 degrees) frequently encountered by the plume from the Westvaco Main Stack within a transport distance of less than 1 kilometer, the performance of the SHORTZ model at the monitors beyond the typical distance to plume stabilization was consistent with previous SHORTZ model performance evaluations and thus tends to support the continued use of the SHORTZ model as a generalized complex terrain dispersion model. However, the SHORTZ model's bias in the Westvaco model evaluation study toward overestimation of concentrations on elevated terrain at distances less than the distance to plume stabilization indicates that the model's predictions should be used with caution and common sense in these situations.

Meteorological Measurements in Complex Terrain

The results of the Westvaco data analysis and model performance evaluation studies clearly demonstrate the critical importance of representative onsite meteorological measurements to develop meteorological inputs for refined complex terrain dispersion models. As discussed by Hanna, *et al*. (1982a), the localized circulations affecting the initial transport and dispersion of the plume from the Westvaco Main Stack are essentially decoupled from the synoptic scale circulation and show virtually no correlation with the wind data from the nearest airport (Greater Pittsburgh Airport). The results of the Westvaco study also show the difficulty of specifying in advance what meteorological measurements are representative for modeling purposes. For example, the purpose of the Beryl Meteorological Tower (see Figure 1-1) was to provide insight to the valley winds experience by the Westvaco plume as it exited the Main Stack. The 100-meter Beryl Tower was so sheltered by the topography during the 2-year monitoring program that over a third of the hourly vector average winds at the 100-meter level were reported as variable or calm. Thus, the Beryl Tower wind data were of no practical value in defining source-receptor relationships during the light wind cases with high observed SO_2 concentrations at the monitors on the ridgeline southeast of the Main Stack. In retrospect, a Doppler acoustic sounder at the site of the Beryl Tower probably would have provided far more meaningful information on stack height winds and turbulent intensities.

The combination of the multilevel 100-meter Tower No. 1 and the multilevel 30-meter Tower No. 2 with tower base elevations ranging from 10 meters below the stack-top elevation (Tower No. 2) to 126 meters above the stack-top elevation (Tower No. 1) enabled the construction of vertical wind, turbulence and temperature profiles. Although the general representativeness of these profiles is not known because of the different locations of the two towers, these profiles were of considerable practical value and were extensively used in the development of meteorological inputs for the SHORTZ and LUMM models. We therefore recommend that future field measurement programs designed to collect data to evaluate complex terrain dispersion models include routine measurements of the vertical profiles of winds, turbulence and temperature. Remote sensing (Doppler acoustic sounders) is probably the most practical way in which to obtain the wind and turbulence profiles.

Monitoring Network Design

The results of the Westvaco model performance evaluation study illustrate how the density and locations of the air quality monitors can significantly affect conclusions about model performance. For example, if only Monitors 8, 9 and 10 had been in place during the 2-year Westvaco monitoring program, the results of the performance evaluation would lead to the unambiguous conclusion that the SHORTZ model provides very accurate estimates of the 25 highest 1-hour, 3-hour and 24-hour average SO_2 concentrations paired in space only, while the LUMM model systematically underestimates these concentrations. On the other hand, if only Monitors

1, 3, 4, 5, 6 and 7 had been in place, the results of the performance evaluation would lead to the unambiguous conclusion that the LUMM model provides very accurate estimates of the 25 highest 1-hour, 3-hour and 24-hour average SO_2 concentrations paired in space only, while the SHORTZ model systematically overestimates these concentrations. It follows that conclusions about model performance that are based on comparisons of observed and calculated concentrations at a single monitor or at a limited number of monitors may not be transferable to other locations in the vicinity of the same source. Additionally, any model that must be calibrated or "tuned" to match the observations at a limited number of monitoring sites cannot be used with confidence at other receptor locations.

(This Page Intentionally Blank)

REFERENCES

Bjorklund, J. R. and J. F. Bowers, 1982: User's instructions for the SHORTZ and LONGZ computer programs. *EPA Reports EPA-903/9-82-004a and 004b (NTIS Accession Numbers PB83-146092 and 146100)*, U. S. Environmental Protection Agency, Region III, Philadelphia, PA.

Briggs, G. A., 1969: *Plume Rise*. Available as TID-25075 from Clearinghouse for Federal Scientific and Technical Information, Springfield, VA, 80.

Briggs, G. A., 1971: Some recent analyses of plume rise observations. *In Proceedings of the Second International Clean Air Congress*. Academic Press, NY.

Briggs, G. A., 1972: Chimney plumes in neutral and stable surroundings. *Atmospheric Environment*, *6*(7), 507-510.

Briggs, G. A., 1973: Diffusion estimates for small emissions. *ATDL Contribution File No. (Draft) 79*, Air Resources Atmospheric Turbulence and Diffusion Laboratory, Oak Ridge, TN.

Briggs, G. A., 1975: Plume rise predictions. *Lectures on Air Pollution and Environmental Impact Analyses*. American Meteorological Society, Boston, MA.

Burt, E. W., 1977: Valley model user's guide. *EPA Report No. EPA-450/2-77-018*, U. S. Environmental Protection Agency, Research Triangle Park, NC.

Burt, E. W. and H. H. Slater, 1977: Evaluation of the Valley model. *Preprint Volume for the Joint Conference on Applications of Air Pollution Meteorology*, American Meteorological Society, Boston, MA, 192-195.

Cramer, H. E., *et al*, 1972: Development of dosage models and concepts. Final Report under Contract DAAD09-67-0020(R) with the U. S. Army, *Deseret Test Center Report DTC-TR-72-609*, Fort Douglas, UT.

Cramer, H. E., H. V. Geary and J. F. Bowers, 1975: Diffusion-model calculations of long-term and short-term ground-level SO_2 concentrations in Allegheny County, Pennsylvania. *EPA Report No. EPA-903/9-75-018 (NTIS Accession No. PB-245262/AS)*, U. S. Environmental Protection Agency, Region III, Philadelphia, PA.

Cramer, H. E., 1976: Improved techniques for modeling the dispersion of tall stack plumes. *Proceedings of the Seventh International Technical Meeting on Air Pollution Modeling and Its Application*, NATO Committee on the Challenges to Modern Society, 731-780.

Cramer Company, H. E., 1981: Westvaco Luke, Maryland monitoring program: Data analysis and dispersion model evaluation (first two quarters). H. E. Cramer Technical Report TR-81-202-01 prepared for the U. S. Environmental Protection Agency under subcontract to Research Triangle Institute, Research Triangle Park, NC.

Environmental Research & Technology, Inc., 1981: Addendum to the report Diffusion Model Development and Evaluation and Emission Limitations at the Westvaco Luke Mill, Environmental Research & Technology, Inc., Concord, MA.

Hanna, S. R., 1982: Private communication (statements made at a 10 September 1982 meeting between representatives of the U. S. Environmental Protection Agency, the State of Maryland and Westvaco Corporation).

Hanna, S., et al., 1982a: Diffusion model development and evaluation and emission limitations at the Westvaco Luke Mill. Document PA439, Environmental Research & Technology, Inc., Concord, MA.

Hanna, S. R., et al., 1982b: An evaluation of the LUMM and SHORTZ dispersion models using the Westvaco data set. Document No. PA-439, Environmental Research & Technology, Inc., Concord, MA.

Pasquill, F., 1976: Atmospheric dispersion-parameters in Gaussian plume modeling. Part II, possible requirements for changes in the Turner Workbook Values. EPA Report No. EPA-600/4-76-3606, U. S. Environmental Protection Agency, Research Triangle Park, NC.

Pierce, T. E. and D. B. Turner, 1980: User's guide for MPTER. EPA Report No. EPA-600/8-80-016, U. S. Environmental Protection Agency, Research Triangle Park, NC.

Turner, D. B., 1964: A diffusion model for an urban area. Journal of Applied Meteorology, 3(1), 83-91.

Turner, D. B., 1970: Workbook of atmospheric dispersion estimates, Publication No. 999-AP-26, National Air Pollution Control Administration, Cincinnati, OH.

Weil, J. C., 1979: Modeling of buoyant plume dispersion in complex terrain. Martin Marietta Corp. Report No. PPRP-35, Martin Marietta Corporation, Baltimore, MD.

Weil, J. C., J. E. Cermak and R. L. Petersen, 1981: Plume dispersion about the windward side of a hill at short range: Wind tunnel vs field measurements. Preprint Volume for the Fifth Symposium on Turbulence, Diffusion and Air Pollution, American Meteorological Society, Boston, MA, 159-160.

APPENDIX A

MODEL EVALUATION PROTOCOL

This appendix contains the protocol for the evaluation of the SHORTZ and LUMM dispersion models using the Westvaco data set that was agreed upon on 21 October 1982 by Westvaco Corporation, the State of Maryland, the U. S. Environmental Protection Agency (EPA) Region III and the EPA Office of Air Quality Planning and Standards (OAQPS).

(This Page Intentionally Blank)

21 October 1982

PROTOCOL FOR THE EVALUATION OF THE SHORTZ AND LUMM DISPERSION MODELS USING THE WESTVACO DATA SET*

1. BACKGROUND AND PURPOSE

The Westvaco data set consists of detailed records of hourly emissions, meteorological and SO_2 air quality data collected in the vicinity of the Westvaco Corporation Paper Mill at Luke, Maryland during the 2-year period December 1979 through November 1981. The purpose of the Westvaco monitoring program was to acquire the data needed to select the most appropriate complex terrain dispersion model for use in establishing an SO_2 emission limitation for the Westvaco Main Stack. Under Contract No. 68-02-3577 with the U. S. Environmental Protection Agency (EPA), the H. E. Cramer Company, Inc. is to use the Westvaco data set to assist in the selection of the complex terrain dispersion model "which provides the best air quality predictions, and which will be the basis for a permanent SO_2 emission limitation." EPA Region III, the EPA Office of Air Quality Planning and Standards (OAQPS), the State of Maryland and Westvaco Corporation have agreed that the two complex terrain dispersion models most likely to be applicable at the Luke Mill are the SHORTZ model and the Luke Mill Model (LUMM). SHORTZ was developed and documented by the H. E. Cramer Company under previous EPA contracts (Cramer, _et al_., 1975; Bjorklund and Bowers, 1982) and LUMM was developed for Westvaco Corporation by Hanna, _et al_. (1982).

The purpose of this Technical Note is to summarize a protocol, agreed upon in advance by EPA Region III, EPA OAQPS, the State of Maryland and Westvaco Corporation, for the evaluation of the two candidate dispersion models as required by the August 1981 EPA report "Interim Procedures for

---

* Technical Note prepared by the H. E. Cramer Company, Inc., Salt Lake City, Utah under Contract No. 68-02-3577 with the U. S. Environmental Protection Agency.

Evaluating Air Quality Models." The August 1981 report suggests that the evaluation of a dispersion model begin with an examination of the specific modeling problem to determine if the current Guideline on Air Quality Models (EPA, 1978) recommends a reference model for the intended type of application. Neither SHORTZ nor LUMM is cited in the current Guideline on Air Quality Models. SHORTZ is arbitrarily defined as the reference model in this model evaluation protocol because of previous applications of the model to the Luke Mill by EPA Region III and the H. E. Cramer Company. The interim procedures recommend that a technical comparison of the proposed model (LUMM) and the reference model (SHORTZ) first be made to determine if the proposed model is qualitatively better than, comparable to, or worse than the reference model. This technical comparison is then followed by a model performance evaluation which focuses on the model performance attributes of concern for the intended application. If the results of the model performance evaluation are inconclusive, the results of the technical evaluation are used to select the most appropriate model. If the results of both the model performance evaluation and the technical evaluation are inconclusive, the Interim Procedures specify the use of the reference model. Because of time and level-of-effort constraints, this protocol addresses only the model performance evaluation.

2. GENERAL APPROACH

Eleven continuous SO_2 monitors were operated in the vicinity of the Westvaco Mill during the 2-year monitoring program. The monitors with the highest observed concentrations were located on elevated terrain in the 90-degree sector southeast of the Westvaco Main Stack (Monitors 1, 3, 4, 5, 6, 7, 8 and 9). Because the distances from the Main Stack to these monitors range from 740 to 1,500 meters, the Westvaco data set principally reflects the concentrations at these relatively short distances. Monitor 10 (Stony Run), which is on elevated terrain 3,400 meters northeast of the Main Stack, is of particular importance because it is the only monitor at the typical distance from the Main Stack to the Westvaco property boundaries. The two other monitors, Monitor 2 and Monitor 11 (Bloomington), are not of major interest for the purpose of dispersion model evaluation for two reasons. First, these monitors generally have the lowest observed concentrations. Second, the distances from the Main Stack to these monitors are within the distance range for the monitors in the sector southeast of the Main Stack. The model performance evaluation is therefore restricted to Monitors 1, 3, 4, 5, 6, 7, 8, 9 and 10.

The SO_2 concentrations of primary concern for regulatory purposes are the maximum annual and the highest of the second-highest 3-hour and 24-hour average concentrations because these concentrations are required to assess compliance with the current National Ambient Air Quality Standards (NAAQS) for SO_2. If there are inadequacies in the available data base, the maximum 3-hour and 24-hour average SO_2 concentrations may also be of concern for regulatory purposes (EPA,1978). Consequently, maximum observed and calculated annual, 3-hour and 24-hour average concentrations and second-highest observed and calculated 3-hour and 24-hour average concentrations will be compared. For consistency with current EPA policy on the enforcement of the NAAQS, the observed and calculated 3-hour and 24-hour average concentrations will be for the standard clock hours and calendar days ("block averages"). The effects of "background" (ambient SO_2 concentrations attributable to sources other than emissions from the Westvaco Main Stack) will be removed from the observed concentrations before performing the comparisons of observed and calculated concentrations. The background concentration during each hour will be defined as the minimum observed concentration if this concentration is above the monitor threshold concentration of 0.005 parts per million (13 micrograms per cubic meter). Because concentrations below 0.005 parts per million are recorded as 0.005 parts per million in the Westvaco data set, the background will be defined as half the monitor threshold concentration (0.0025 parts per million or 6.5 micrograms per cubic meter) if the minimum observed concentration is recorded as 0.005 parts per million.

The possible pairings of observed and calculated concentrations for the purpose of model evaluation include (Fox, 1981): (1) maximum or total fields of observed and calculated concentrations paired in space and time, (2) maximum observed and calculated concentrations paired in time only, (3) maximum observed and calculated concentrations paired in space only, and (4) maximum observed and calculated concentrations unpaired in either space or time. Because of limitations and uncertainties in model source and meteorological inputs, it is not feasible to model the highest short-term concentrations paired in space and time. Consequently, only annual average concentrations paired in space and time will be compared. (The air quality data will be used to determine the location of the maximum annual average concentrations paired in space and time.) Model evaluations of maximum concentrations paired in time only are based on the premise that the model can predict the magnitude of the maximum concentration during any time period with greater accuracy than it can predict the location of the maximum concentration. For example, an uncertainty in the transport wind direction of only a few degrees can lead to large errors in the hourly concentrations calculated at fixed monitor locations in spite of the fact that the model may accurately predict the maximum concentrations at the downwind distances of the monitors (see Figures E-2 and E-3 of Cramer, et al. 1976). Assuming a "perfect model," the highest short-term concentrations calculated over a long period of record at fixed monitor locations should be in good agreement with the highest concentrations observed during the same period if the uncertainties in the model's source and meteorological inputs are random rather than systematic. For this reason, this protocol includes a comparison at each monitor of interest of: (1) the maximum and second-highest 3-hour and 24-hour average observed and calculated concentrations unpaired in time, and (2) the 25 highest 1-hour, 3-hour and 24-hour average observed and calculated concentrations unpaired in time. In addition to the comparisons of the highest short-term concentrations paired in space only, the 25-highest 1-hour, 3-hour and 24-hour average observed and calculated concentrations unpaired in space or time will be compared because these concentrations are of practical importance in regulatory decisions.

3. SHORTZ MODEL MODIFICATIONS FOR USE IN THE WESTVACO STUDY

SHORTZ differs from LUMM in that SHORTZ is a generalized model designed for application to single or multiple sources in regions of complex terrain, whereas LUMM is a single-source model specifically designed for application to the Westvaco Luke Mill. It has been the experience of the H. E. Cramer Company that the "universal function" implicit in the SHORTZ equation for the lateral dispersion coefficient σ_y adequately accounts for the effects of vertical wind-direction shear on lateral plume expansion in most situations (Bjorklund and Bowers, 1982, p. 2-33). However, based on an examination of the hourly wind-direction and SO_2 concentration measurements from the first two quarters of the Westvaco monitoring program, the H. E. Cramer Company (January 1981) reported to EPA Region III that the plume from the Westvaco Main Stack is subject to very large vertical wind-direction shears as it rises through the highly channeled valley flow and enters the flow above the elevated terrain. Because of these large wind-direction shears, our January 1981 report suggested that it would be appropriate to modify SHORTZ for application to the Luke Mill by inclusion of the Cramer, _et al_. (1972) technique for accounting for the effects of vertical wind-direction shear on crosswind plume expansion. Following this approach, the total lateral dispersion coefficient σ_{yT} is given by

$$\sigma_{yT} = \left[\sigma_y^{\,2} + \left(\frac{\Delta\theta' x}{4.3}\right)^2\right]^{1/2} \qquad (1)$$

where σ_y is the unmodified SHORTZ lateral dispersion coefficient, x is the downwind distance and $\Delta\theta'$ is the wind-direction shear in radians for the layer containing the plume. We also concluded in our January 1981 report that the difference in wind direction between the upper levels of Tower No. 1 and Tower No. 2 (the Luke Hill Tower) probably provides the best available objective indicator of $\Delta\theta'$. We therefore developed a modified version of SHORTZ for use in the Westvaco model evaluation effort that incorporates Equation (1). Parenthetically, Hanna, _et al_. (1982) independently arrived at similar conclusions about how best to account for the effects of vertical wind-direction shear in LUMM.

4. MODEL INPUTS

Hourly Meteorological Inputs

In the opinion of Westvaco Corporation, the hourly meteorological inputs previously developed by Hanna, et al. (1982) for use with LUMM are an integral part of LUMM. Because EPA has accepted Westvaco's contention, the LUMM hourly meteorological inputs for use in the model evaluation will be as defined in Table A-1 of the Hanna, et al. (1982) report except that the set of artificial north winds will be removed. The SHORTZ hourly meteorological inputs discussed below were selected to minimize any modifications of the onsite measurements or substitutions for missing data in order to preserve the scientific objectivity and validity of the model evaluation.

The primary SHORTZ hourly meteorological inputs for use in the model evaluation are listed in Table 1. Previous work indicates that the wind-direction measurements most representative of the transport wind directions vary with the meteorological conditions. If, for simplicity, wind directions from only one tower and level are selected for use in the model calculations, we believe that the wind directions from the 100-meter level of Tower No. 1 are most representative of the transport wind directions for all meteorological conditions. Although the 10-meter level of Tower No. 2 is closest to the elevation of the top of the Main Stack, this level is likely sheltered by local roughness elements and terrain during hours with winds toward the monitoring network. Consequently, we have selected the 30-meter level of Tower No. 2 to obtain the SHORTZ reference level wind speeds. As noted in Section 3, we will use the wind-direction difference between the upper levels of Towers No. 1 and No. 2 to estimate vertical wind-direction shear for use in the modified SHORTZ calculations. The wind-profile exponents will be estimated from the differences in wind speed between the upper levels of the two towers, while the vertical potential temperature gradients will be based on the differences in temperature between the top of Tower No. 1 and the 10-meter level of Tower No. 2. The ambient air temperatures used in the plume rise calculations will be from

TABLE 1

PRIMARY SHORTZ HOURLY METEOROLOGICAL INPUTS

Input Parameter	Primary Source
Transport Wind Direction	100m Level of Tower No. 1
Reference Level Wind Speed	30m Level of Tower No. 2 (Luke Hill Tower)
Vertical Wind-Direction Shear	Direction Difference between Upper Levels of Towers No. 1 and No. 2
Wind-Profile Exponent	Based on Speed Difference between Upper Levels of Tower No. 1 and No. 2
Vertical Potential Temperature Gradient	Based on Temperature Difference between 10m Level of Tower No. 2 and 100m Level of Tower No. 1
Ambient Air Temperature	10m Level of Tower No. 2
Lateral and Vertical Turbulent Intensities	30m Level of Tower No. 2
Mixing Depths	A constant value of 1000m

the 10-meter level of Tower No. 2. Because Tower No. 2 is upwind of the Main Stack during hours with winds toward the main monitoring network, we believe that the turbulent intensities from the 30-meter level of this tower are most likely to be representative of the turbulence affecting the plume. Based on a comparison of onsite minisonde measurements, tower temperature measurements and acoustic sounder measurements, we previously concluded that the acoustic sounder mixing depths are invalid--a conclusion also reached by Hanna, et al. (1982). It is our opinion from an examination of the Westvaco data set and preliminary SHORTZ calculations that the plume from the Main Stack is almost always contained within the surface mixing layer and that the restriction on vertical mixing usually has no effect on the ground-level concentrations at the short downwind distances of the air quality monitors. Consequently, in the absence of satisfactory measurements of mixing depths, we will assume a constant mixing depth of 1,000 meters in the SHORTZ calculations.

We searched the Westvaco data set to see how many hours during each year of the 2-year monitoring program would require no data substitutions if we used the primary hourly meteorological inputs in Table 1. Complete primary hourly inputs are available for 3,608 hours during the first year and for 5,282 hours during the second year. If calendar days are considered, complete hourly inputs are available for 20 days during the first year and for 140 days during the second year. Because of the extremely large number of hours of missing meteorological data during the first year, only the second year will be considered in the model evaluation using data substitutions as shown in Table 2. Although we have serious reservations about the use of data substitutions because they raise serious questions about the validity of any conclusions that might be reached about model performance, we believe the data substitutions listed in Table 2 comprise the most objective procedure for developing a complete set of hourly meteorological inputs for the second year of data.

TABLE 2

DATA SUBSTITUTIONS TO BE USED IN DEVELOPING SHORTZ HOURLY METEOROLOGICAL INPUTS

Input Parameter	Rank of Parameter Source	Parameter Source
Transport Wind Direction[1]	1	100m Level of Tower No. 1
	2	50m Level of Tower No. 1
	3	10m Level of Tower No. 1
	4	30m Level of Tower No. 2
	5	10m Level of Tower No. 2
Reference Level Wind Speed[2]	1	30m Level of Tower No. 2
	2	10m Level of Tower No. 1
	3	50m Level of Tower No. 1
	4	100m Level of Tower No. 1
	5	10m Level of Tower No. 2
Vertical Wind-Direction Shear[3]	1	Direction Difference between 100m Level of Tower No. 1 and 30m Level of Tower No. 2
	2	Direction Difference between 50m Level of Tower No. 1 and 30m Level of Tower No. 2
	3	Direction Difference between 10m Level of Tower No. 1 and 30m Level of Tower No. 2
	4	Direction Difference between 100m Level of Tower No. 1 and 10m Level of Tower No. 2
	5	Direction Difference between 50m Level of Tower No. 1 and 10m Level of Tower No. 2
	6	Direction Difference between 10m Level of Tower No. 1 and 10m Level of Tower No. 2
	7	Direction Difference between 100m and 10m Levels of Tower No. 1
	8	Direction Difference between 50m and 10m Levels of Tower No. 1
Wind-Profile Exponent[4]	1	Based on Speed Difference between 100m Level of Tower No. 1 and 30m Level of Tower No. 2

TABLE 2 (Continued)

Input Parameter	Rank of Parameter Source	Parameter Source
Wind-Profile Exponent[4] (Continued)	2	Based on Speed Difference between 50m Level of Tower No. 1 and 30m Level of Tower No. 2
	3	Based on Speed Difference between 10m Level of Tower No. 1 and 30m Level of Tower No. 2
	4	Based on Speed Difference between 100m Level of Tower No. 1 and 10m Level of Tower No. 2
	5	Based on Speed Difference between 50m Level of Tower No. 1 and 10m Level of Tower No. 2
	6	Based on Speed Difference between 10m Level of Tower No. 1 and 10m Level of Tower No. 2
	7	Based on Speed Difference between 100m and 10m Levels of Tower No. 1
	8	Based on Speed Difference between 50 and 10m Levels of Tower No. 1
Vertical Potential Temperature Gradient[5]	1	Based on Temperature Difference between 100m Level of Tower No. 1 and 10m Level of Tower No. 2
	2	Based on Temperature Difference between 10m Level of Tower No. 1 and 10m Level of Tower No. 2
	3	Based on Temperature Difference between 100m and 10m Levels of Tower No. 1
	4	Based on Temperature Difference between 30m and 10m Levels of Tower No. 2
Ambient Air Temperature	1	10m Level of Tower No. 2
	2	10m Level of Tower No. 1
	3	10m Level of Beryl Tower
Lateral and Vertical Turbulent Intensities[6]	1	30m Level of Tower No. 2
	2	10m Level of Tower No. 1
	3	50m Level of Tower No. 1
	4	100m Level of Tower No. 1
	5	10m Level of Tower No. 2

TABLE 2 (Continued)

[1] If no non-variable wind direction is found, the hour will be flagged by setting the wind direction equal to 090 degrees and the mixing depth equal to 1 meter.

[2] Wind speeds above 0, but less than 1 meter per second, will be set equal to 1 meter per second. If all of the wind speeds are calm, the hour will be flagged by setting the wind direction equal to 090 degrees and the mixing depth equal to 1 meter.

[3] If none of the data substitutions is possible, the wind-direction shear will be set equal to zero.

[4] The wind-profile exponent will be set equal to zero if the calculated exponent is negative or if none of the data substitutions is possible. The wind-profile exponent will not be allowed to exceed unity.

[5] If none of the data substitutions is possible, the vertical potential temperature gradient will be set equal to the moist adiabatic value of 0.003 degrees Kelvin per meter.

[6] If no turbulence measurements are available, the lateral and/or vertical turbulent intensities entered will be climatological values for the combination of season, wind-speed and time-of-day categories.

The wind-profile exponents for use in the SHORTZ calculations will be based on the model's assumption that the wind speed at height z above mean sea level is given by

$$\bar{u}\{z\} = \left\{ \begin{array}{ll} \bar{u}_R \left(\dfrac{z-z_a}{z_R} \right)^p & ; \; z \geq z_a + z_R \\ \bar{u}_R & ; \; z < z_a + z_R \end{array} \right\} \qquad (2)$$

where $\bar{u}_R$ is the wind speed at height z_R above the surface at a point with elevation z_a above mean sea level. In the SHORTZ calculations, z_a will be defined as the elevation at the base of Tower No. 2 (468 meters MSL) and z_R will be defined as the Tower No. 2 wind-speed measurement height of 30 meters above ground level. The first line of Equation (2) may be rewritten as

$$p = \frac{\ell n(\bar{u}_2/\bar{u}_1)}{\ell n(z_2/z_1)} \qquad (3)$$

with $\bar{u}_2$, $\bar{u}_1$, z_2 and z_1 as defined in Table 3 for the eight possible combinations of wind-speed inputs. As shown by Table 3, z_1 is the height above ground level at which $\bar{u}_1$ is measured and -- for the first six choices of wind-speed inputs -- z_2 is the height above the base of Tower No. 2 at which $\bar{u}_2$ is measured. Wind-speed measurements from Tower No. 1 alone are used for the last two choices of wind-speed inputs, and z_2 for these choices is the height above the base of Tower No. 1 at which $\bar{u}_2$ is measured.

TABLE 3

WIND SPEEDS AND EFFECTIVE HEIGHTS Z_1 AND Z_2 USED TO CALCULATE WIND-PROFILE EXPONENTS FOR USE WITH SHORTZ

Rank of Wind-Speed Source	Source of $\bar{u}_2$ in Equation (3)	Source of $\bar{u}_1$ in Equation (3)	Heights z_2 and z_1 in Equation (3)	
			z_2 (m)	z_1 (m)
1	100m Level of Tower No. 1	30m Level of Tower No. 2	232	30
2	50m Level of Tower No. 1	30m Level of Tower No. 2	182	30
3	10m Level of Tower No. 1	30m Level of Tower No. 2	142	30
4	100m Level of Tower No. 1	10m Level of Tower No. 2	232	10
5	50m Level of Tower No. 1	10m Level of Tower No. 2	182	10
6	10m Level of Tower No. 1	10m Level of Tower No. 2	142	10
7	100m Level of Tower No. 1	10m Level of Tower No. 1	100	10
8	50m Level of Tower No. 1	10m Level of Tower No. 1	50	10

The vertical potential temperature gradients will be calculated from the onsite tower temperature measurements using the general expression

$$\frac{\partial\theta}{\partial z}\ (^\circ K/m) = \frac{(T_2(^\circ K) - T_1(^\circ K))}{(z_2 - z_1)} + 0.01 \qquad (4)$$

Table 4 identifies T_2, T_1 and (z_2-z_1) for the four choices of temperature measurements shown in Table 2.

As noted by the sixth footnote at the bottom of Table 2, we will use climatological values of the vertical and/or lateral turbulent intensities for the hours with no onsite turbulence measurements. We analyzed the wind-speed and turbulence data from the 30-meter level of Tower No. 2 during the second year of the Westvaco monitoring program to determine median turbulent intensities for each combination of season (winter, spring, summer and fall), wind-speed category and time-of-day category. The seasons were defined in the conventional sense for dispersion modeling. For example, winter was comprised of December, January and February. Time of day was based on sunrise and sunset and was defined as follows:

- Morning - Sunrise plus 1 hour to sunrise plus 5 hours
- Afternoon - Sunrise plus 5 hours to sunset minus 1 hour
- Evening - Sunset minus 1 hour to sunset plus 2 hours
- Night - Sunset plus 2 hours to sunrise plus 1 hour

The resulting median lateral and vertical turbulent intensities are listed in Tables 5 and 6, respectively.

We point out that, if the wind during an hour is calm or variable at all levels of Tower No. 1 and Tower No. 2, we will define the calculated

TABLE 4

AMBIENT AIR TEMPERATURES AND HEIGHT INTERVALS USED TO CALCULATE VERTICAL POTENTIAL TEMPERATURE GRADIENTS FOR USE WITH SHORTZ

Rank of Temperature Source	Source of T_2 in Equation (4)	Source of T_1 in Equation (4)	Height Interval $(z_2 - z_1)$ (m)
1	100m Level of Tower No. 1	10m Level of Tower No. 2	222
2	10m Level of Tower No. 1	10m Level of Tower No. 2	132
3	100m Level of Tower No. 1	10m Level of Tower No. 1	90
4	30m Level of Tower No. 2	10m Level of Tower No. 2	20

TABLE 5

MEDIAN HOURLY LATERAL TURBULENT INTENSITIES AT THE 30-METER LEVEL OF TOWER NO. 2 DURING THE SECOND YEAR OF THE WESTVACO MONITORING PROGRAM

Time of Day	Wind Speed (m/sec)					
	0-1.5	1.6-3.1	3.2-5.1	5.2-8.2	8.3-10.8	10.8
(a) Winter						
Night	0.45	0.15	0.25	0.25	0.25	0.25
Morning	0.40	0.25	0.25	0.25	0.25	0.25
Afternoon	0.50	0.25	0.25	0.25	0.25	0.25
Evening	0.55	0.25	0.25	0.25	0.25	0.25
(b) Spring						
Night	0.45	0.25	0.15	0.25	0.25	*
Morning	0.60	0.25	0.25	0.25	0.25	*
Afternoon	0.70	0.45	0.35	0.30	0.25	0.25
Evening	0.55	0.35	0.25	0.25	0.25	*
(c) Summer						
Night	0.45	0.15	0.15	0.20	0.25	*
Morning	0.55	0.25	0.25	0.25	0.25	*
Afternoon	0.70	0.35	0.35	0.25	0.25	*
Evening	0.60	0.25	0.15	0.25	*	*
(d) Fall						
Night	0.40	0.15	0.15	0.25	0.25	*
Morning	0.45	0.25	0.25	0.25	0.25	0.25
Afternoon	0.65	0.35	0.25	0.25	0.25	0.25
Evening	0.55	0.25	0.25	0.25	0.25	*

* No observations.

TABLE 6

MEDIAN HOURLY VERTICAL TURBULENT INTENSITIES AT THE 30-METER LEVEL OF TOWER NO. 2 DURING THE SECOND YEAR OF THE WESTVACO MONITORING PROGRAM

Time of Day	Wind Speed (m/sec)					
	0-1.5	1.6-3.1	3.2-5.1	5.2-8.2	8.3-10.8	10.8
(a) Winter						
Night	0.05	0.05	0.15	0.15	0.15	0.15
Morning	0.15	0.15	0.15	0.15	0.15	0.15
Afternoon	0.25	0.15	0.15	0.15	0.15	0.15
Evening	0.10	0.15	0.15	0.15	0.15	0.15
(b) Spring						
Night	0.05	0.05	0.10	0.15	0.15	*
Morning	0.30	0.15	0.15	0.15	0.15	*
Afternoon	0.35	0.15	0.15	0.15	0.15	0.15
Evening	0.15	0.15	0.15	0.15	0.15	*
(c) Summer						
Night	0.05	0.05	0.05	0.15	0.15	*
Morning	0.20	0.15	0.15	0.15	0.15	*
Afternoon	0.40	0.15	0.15	0.15	0.15	*
Evening	0.15	0.05	0.05	0.15	*	*
(d) Fall						
Night	0.05	0.05	0.05	0.15	0.15	*
Morning	0.15	0.15	0.15	0.15	0.15	0.15
Afternoon	0.25	0.15	0.15	0.15	0.15	0.15
Evening	0.05	0.05	0.15	0.15	0.30	*

* No observations.

ground-level concentrations for the hour as missing. Also, a calculated 3-hour concentration must contain 3 hours of non-missing calculated hourly concentrations to be considered, while a 24-hour concentration must contain 18 hours of non-missing calculated hourly concentrations to be considered. For example, a 24-hour period with 3 calm (missing) hours will have a "24-hour average concentration" defined by the 21-hour average concentration for the 21 hours of non-calm winds. We will use the same procedure for hours with missing concentration measurements to obtain the highest observed 3-hour and 24-hour average concentrations. Calm winds during hours with valid concentration measurements will have no effect on our determination of the highest observed 1-hour, 3-hour and 24-hour average concentrations.

Source Inputs

Table 7 gives the stack height, stack radius, Universal Transverse Mercator (UTM) X and Y coordinates and stack base elevation for the Westvaco Main Stack. The other critical SHORTZ hourly source input parameters are the SO_2 emission rate, the actual volumetric emission rate and the stack exit temperature. The Westvaco data set includes hourly measurements of the stack exit temperature, the SO_2 emission rate in tons per hour and the in-stack SO_2 concentration in parts per million. We will use these parameters to compute the actual volumetric emission rate (stack gas flow rate) from the expression

$$V(m^3/sec) = \frac{322.9\ Q_{SO_2}(ton/hr) \cdot T_s(°K)}{\rho_{SO_2}(ppm)} \qquad (5)$$

where Q_{SO_2} is the SO_2 emission rate, T_s is the stack exit temperature and ρ_{SO_2} is the in-stack SO_2 concentration. If an hourly SO_2 emission rate, volumetric emission rate or stack exit temperature is missing, we will use the last reported value.

TABLE 7

WESTVACO STACK PARAMETERS

Parameter	Parameter Value
Stack Height (m)	189.7
Stack Radius (m)	1.68
Stack Coordinates	
UTM X (m)	667,091
UTM Y (m)	4,370,759
Stack Base Elevation (m MSL)	288

Receptor and Other Inputs

Table 8 gives the UTM X and Y coordinates and elevations of the nine air quality monitors to be considered in the model performance evaluation. Although not shown in Table 7, the hourly concentration measurements from Monitor 2 (Luke Hill) and Monitor 11 (Bloomington) in addition to the hourly concentration measurements from the monitoring sites identified in Table 7 will be used to estimate background concentrations (see Section 3).

SHORTZ is a highly generalized dispersion model with a large number of input and output options. Although detailed SHORTZ user's instructions are given by Bjorklund and Bowers (1982), we believe that is is important to identify the values of some of the critical program control parameters and model constants for use in the Westvaco model evaluation. As shown by Table 9, SHORTZ will in general be executed in its default mode. Because the SO_2 emission rate will be entered in grams per second, the units conversion factor TK will be set equal to 381.68 to obtain concentrations in parts per million. (The default value of TK is 10^6 for concentrations in micrograms per cubic meter.) The elevation above mean sea level of Tower No. 2 of 468 meters is defined in Table 9 as the weather station elevation. The wind measurement height ZR is 30 meters, the height above ground level of the upper level of Tower No. 2.

5. MEASURES OF MODEL PERFORMANCE

To the best of our knowledge, the only study to date which fully addresses the proposed AMS Measure of Dispersion Model Performance is the study by Londergan, et al. (1982), who note that (p. 64):

> One conclusion is apparent from even a cursory inspection of the ... tables. The volume of model performance statistics which was generated in this study is excessive. The amount of effort required to analyze fully the information contained in these tables is prohibitive. After a limited review, it is also apparent that many of the statistics are relatively uninformative,

TABLE 8

UNIVERSAL TRANSVERSE MERCATOR (UTM) X AND Y COORDINATES AND ELEVATIONS ABOVE MEAN SEA LEVEL (MSL) OF THE AIR QUALITY MONITORING SITES

Site	Coordinates		Ground Elevation (m MSL)
	UTM X (m)	UTM Y (m)	
1	667,800	4,370,360	604
3	667,638	4,370,259	564
4	667,639	4,370,060	603
5	667,576	4,369,729	639
6	667,860	4,370,604	591
7	667,320	4,369,780	637
8	667,090	4,369,277	643
9	667,412	4,369,278	673
10 (Stony Run)	669,766	4,372,851	504

TABLE 9
SHORTZ PROGRAM CONTROL PARAMETERS AND MODEL CONSTANTS FOR USE IN THE WESTVACO MODEL EVALUATION STUDY

SHORTZ Input Parameter	Meaning of Parameter	Parameter Value for the Westvaco Model Evaluation Study
ISW (7)	Define as "1" if Terrain Elevations Are Used	1
ISW (9)	Define as "1" for Wind Speed a Function of Height AGL Rather Than Height MSL	0 (Default Value)
TK	Units Conversion Factor	381.68 (Concentration in ppm)
ZR	Wind Speed Measurement Height Above HA (m)	30
HA	Elevation above MSL of Weather Station	467.57
GAMMA 1	Adiabatic Plume Rise Entrainment Coefficient	0.60 (Default Value)
GAMMA 2	Stable Plume Rise Entrainment Coefficient	0.66 (Default Value)
XRY	Distance Over Which Rectilinear Lateral Expansion Occurs (m)	50 (Default Value)
ALPHA	Lateral Diffusion Coeffient	0.9 (Default Value)
DECAY	Exponential Decay Coefficient (sec^{-1})	0 (Default Value)
ROTATE	Angular Displacement of Receptor Grid from True North	0 (Default Value)

> repetitious, and redundant. It is not very productive to demonstrate, eight times over, many of the general performance characteristics... In an effort to follow the AMS workshop recommendations as closely as possible, TRC and EPA elected to implement the full list of performance measures for all the data sets and subsets specified. A thorough review of this final report is warranted, with the goal of setting priorities and evaluating the usefulness of various measures, in order to provide greater flexibility and better focus for future model evaluation exercises.

In view of these comments and our experience to date with the AMS Measures of Performance (Bowers, 1982; Bowers, et al., 1982), this protocol considers only a meaningful subset of the AMS Measures of Performance.

Of the numerous AMS Measures of Performance, this protocol uses two parametric measures. The first measure of performance is the bias (average difference between observed and calculated concentrations), which is defined as

$$\overline{\Delta\chi} = \frac{1}{N} \sum_{i=1}^{N} \Delta\chi_i \qquad (6)$$

$$\Delta\chi_i = \chi_{oi} - \chi_{ci} \qquad (7)$$

where χ_{oi} is the i^{th} observed concentration, χ_{ci} is the i^{th} calculated concentration and N is the number of paired observed and calculated concentrations. The second measure of performance is a measure of the "noise" in the results of the model calculations and is provided by the variance of the differences

$$\sigma^2 = \frac{1}{N-1} \sum_{i=1}^{N} (\Delta\chi_i - \overline{\Delta\chi})^2 \qquad (8)$$

The August 1981 draft EPA report "Interim Procedures for Evaluating Air Quality Models" recommends that a model performance evaluation plan be developed in advance of any model testing. This plan assigns to the various measures of model performance specific numerical values (points) which are dependent on the objectives of the model calculations. For example, a first-order objective might be to determine which model best predicts the highest concentrations that are required for regulatory decision making and a second-order objective might be to determine which model best predicts total concentration fields. This model evaluation protocol has a single objective, the determination of the best model to be used to establish an SO_2 emission limitation for the Westvaco Mill. As noted in Section 2, the Westvaco data set is heavily weighted by concentrations on Westvaco property at a downwind distance from the Main Stack of about 1 kilometer (eight out of nine monitors). Monitor 10 (Stony Run) is the only monitor at the typical downwind distance of the Westvaco property boundaries. Because it is our understanding that the SO_2 concentrations calculated at and beyond the Westvaco property boundaries are of primary concern for regulatory purposes, comparisons of concentrations paired in space at Monitor 10 are assigned possible points in this protocol that are four times the corresponding possible points assigned to each of the eight other monitors.

Table 10 gives the pairings of observed and calculated concentrations, measures of performance and the points to be assigned to the various comparisons of observed and calculated concentrations. The score for each pairing of maximum and second-highest observed and calculated concentrations is based on the absolute value of the residual $|\Delta\chi|$ and is given by

$$\{\text{Score Model}_i\} = \frac{|\Delta\chi|\text{min}}{|\Delta\chi_i|} \times \text{MIN}\{C_i/O\ ,O/C_i\} \times \{\text{Possible Points}\} \tag{9}$$

TABLE 10

PAIRINGS OF OBSERVED AND CALCULATED CONCENTRATIONS, MEASURES OF PERFORMANCE AND POSSIBLE POINTS

Concentrations	Paired In		Measure of Performance	Averaging Time	Possible Points
	Space	Time			
Maximum	No	No	$\lvert\Delta\chi\rvert$[1]	3 Hours	20
				24 Hours	20
	Yes	No	$\lvert\Delta\chi\rvert$[1]	3 Hours	2/Monitor[2]
				24 Hours	2/Monitor[2]
	No	Yes	$\lvert\Delta\chi\rvert$[1]	Annual	20
	Yes	Yes	$\lvert\Delta\chi\rvert$[1]	Annual	20
Second-Highest	No	No	$\lvert\Delta\chi\rvert$[1]	3 Hours	30
				24 Hours	30
	Yes	No	$\lvert\Delta\chi\rvert$[1]	3 Hours	3/Monitor[2]
				24 Hours	3/Monitor[2]
25 Highest	No	No	Bias	1 Hour	25[3]
				3 Hours	25[3]
				24 Hours	25[3]
			Variance	1 Hour	5[4]
				3 Hours	5[4]
				24 Hours	5[4]

TABLE 10 (Continued)

Concentrations	Paired In		Measure of Performance	Averaging Time	Possible Points
	Space	Time			
	Yes	No	Bias	1 Hour	5/Monitor[2,3]
				3 Hours	5/Monitor[2,3]
				24 Hours	5/Monitor[2,3]
			Variance	1 Hour	2/Monitor[2,4]
				3 Hours	2/Monitor[2,4]
				24 Hours	2/Monitor[2,4]

[1] The score is given by the possible points multiplied by: (1) the ratio of the absolute value of the minimum residual $|\Delta\chi|$ for either model to the absolute value of the residual for the model being evaluated, and (2) the minimum of the ratio of calculated and observed concentrations (C/O) and the ratio of observed and calculated concentrations (O/C) for the model being evaluated. The score is rounded to the nearest integer.

[2] Because eight of the nine monitors are located on Westvaco property at approximately the same distance from the Westvaco Main Stack, the possible points for the more distant and off-property Monitor 10 are four times those shown for the other monitors.

[3] The scoring system is the same as for the maximum and second-highest concentrations except that absolute values of biases are substituted for absolute values of residuals and average concentrations are substituted for maximum or second-highest concentrations.

[4] The score is given by the possible points multiplied by the minimum of the ratio of the variances for the observed and calculated concentrations and the ratio of the variances for the calculated and observed concentrations.

where

$|\Delta\chi|\text{min}$ = the absolute value of the minimum residual for either model

$|\Delta\chi_i|$ = the absolute value of the residual for the i^{th} model

$\text{MIN}\{C_i/O, O/C_i\}$ = the minimum for the i^{th} model of the ratio of calculated and observed concentrations (C/O) and the ratio of observed and calculated concentrations (O/C)

The score calculated from Equation (9) is rounded to the nearest integer. It follows from Equation (9) that the only model with the potential to be awarded all of the possible points is the model with the minimum residual. The first of the scores for each pairing of the 25 highest observed and calculated concentrations is also given by Equation (9) with biases substituted for residuals and average concentrations substituted for maximum or second-highest concentrations. The second of the scores for each pairing of the 25 highest observed and calculated short-term concentrations is given by

$$\{\text{Score Model}_i\} = \text{MIN}\{\sigma_{ci}^2/\sigma_o^2, \sigma_o^2/\sigma_{ci}^2\} \times \{\text{Possible Points}\} \qquad (10)$$

where

σ_{ci}^2 = the variance of the calculated concentrations for the i^{th} model

σ_o^2 = the variance of the observed concentrations

The score calculated from Equation (10) is also rounded to the nearest integer.

Table 11 shows the computation of the maximum possible points from Table 10 and Table 12 gives the allocation of these points by model performance attribute. Of the 602 possible points overall, 260 points (about 43 percent) are assigned to the concentration comparisons of concern for regulatory decision makers (the maximum annual and short-term average concentrations and the second-highest short-term average concentrations). Of the 372 possible points overall for the maximum, second-highest and 25 highest short-term concentrations paired in space only, 124 points are assigned to Monitor 10 because it is the only monitor at the typical distance of concern for setting an SO_2 emission limitation. We have assigned 75 percent of the 342 available points for the 25 highest concentrations paired in space only and unpaired in space or time to absence of bias because we consider absence of bias in dispersion model predictions to be of critical importance. More points are allocated to the two measures of performance for the 25 highest short-term concentrations paired in space only than to the performance measures for the 25 highest short-term concentrations unpaired in space or time because we believe that the comparisons of the highest concentrations paired in space are scientifically more significant than the comparisons of the the highest unpaired concentrations. The model to be used in the dispersion model calculations to set an SO_2 emission limitation for the Westvaco Mill will be the model with the highest score.

TABLE 11

COMPUTATION OF MAXIMUM POSSIBLE POINTS FROM TABLE 10

Concentrations	Paired In		Measure of Performance	Computation of Possible Points
	Space	Time		
Maximum	No	No	$\|\Delta\chi\|$	20 points x 2 averaging times = 40 points
	Yes	No	$\|\Delta\chi\|$	2 points x 2 averaging times x 8 monitors = 32 points
				8 points x 2 averaging times for Monitor 10 = 16 points
	No	Yes	$\|\Delta\chi\|$	20 points x 1 averaging time = 20 points
	Yes	Yes	$\|\Delta\chi\|$	20 points x 1 averaging time = 20 points
Second-Highest	No	No	$\|\Delta\chi\|$	30 points x 2 averaging times = 60 points
	Yes	No	$\|\Delta\chi\|$	3 points x 2 averaging times x 8 monitors = 48 points
				12 points x 2 averaging times for Monitor 10 = 24 points
25 Highest	No	No	Bias	25 points x 3 averaging times = 75 points
			Variance	5 points x 3 averaging times = 15 points
	Yes	No	Bias	5 points x 3 averaging times x 8 monitors = 120 points
				20 points x 3 averaging times for Monitor 10 = 60 points
			Variance	2 points x 3 averaging times x 8 monitors = 48 points
				8 points x 3 averaging times for Monitor 10 = 24 points
				Maximum Possible Points 602

TABLE 12

ALLOCATION OF POSSIBLE POINTS ACCORDING TO MODEL PERFORMANCE ATTRIBUTE

Model Performance Attribute	Possible Points	Percent of Maximum Possible Points
Ability to Predict Maximum 3-Hour and 24-Hour Average Concentrations Unpaired in Space or Time	40	7
Ability to Predict Maximum 3-Hour and 24-Hour Average Concentrations Paired in Space Only	48	8
Ability to Predict Maximum Annual Average Concentrations Paired in Space and Time or in Time Only	40	7
Ability to Predict Second-Highest 3-Hour and 24-Hour Average Concentrations Unpaired in Space or Time	60	10
Ability to Predict Second-Highest 3-Hour and 24-Hour Average Concentrations Paired in Space Only	72	12
Absence of Bias in Predicting the 25 Highest Short-Term Concentrations Unpaired in Space or Time	75	12
Absence of Bias in Predicting the 25 Highest Short-Term Concentrations Paired in Space Only	180	30
Variances of 25 Highest Observed and Calculated Short-Term Concentrations Unpaired in Space or Time Do Not Differ	15	2
Variances of 25 Highest Observed and Calculated Short-Term Concentrations Paired in Space Only Do Not Differ	72	12
Total	602	100

REFERENCES

Bjorklund, J. R. and J. F. Bowers, 1982: User's instructions for the SHORTZ and LONGZ computer programs. EPA Reports EPA-903/9-82-004a and 004b (in publication), U. S. Environmental Protection Agency, Region III, Philadelphia, PA.

Bowers, J. F., 1982: Scientific review of the ten rural dispersion models under consideration by the U. S. Environmental Protection Agency for possible inclusion in the next Guideline on Air Quality Models. Paper prepared for the AMS Steering Committee for the cooperative agreement between the American Meteorological Society and the U. S. Environmental Protection Agency.

Bowers, J. F., A. J. Anderson and W. R. Hargraves, 1982: Tests of the Industrial Source Complex (ISC) Dispersion Model at the Armco Middletown, Ohio Steel Mill. EPA Report No. EPA-450/4-82-006 prepared for U. S. Environmental Protection Agency, Research Triangle Park, NC.

Cramer, H. E., et al., 1972: Development of dosage models and concepts. Final Report under Contract DAAD09-67-C-0020(R) with the U. S. Army, Deseret Test Center Report DTC-TR-72-609, Fort Douglas, UT.

Cramer, H. E., H. V. Geary and J. F. Bowers, 1975: Diffusion-model calculations of long-term and short-term ground-level SO_2 concentrations in Allegheny County, Pennsylvania. EPA Report 903/9-75-018 (NTIS Accession No. PB 245262/AS), U. S. Environmental Protection Agency, Region III, Philadelphia, PA.

Cramer, H. E., J. F. Bowers and H. V. Geary, 1976: Assessment of the air quality impact of SO_2 emissions from the ASARCO-Tacoma smelter. EPA Report No. EPA 910/9-76-028, U. S. Environmental Protection Agency, Region X, Seattle, WA.

Cramer Company, H. E., 1981: Westvaco Luke, Maryland monitoring program: Data analysis and dispersion model evaluation (first two quarters). H. E. Cramer Company, Inc. Technical Report TR-81-202-01 prepared for the U. S. Environmental Protection Agency under subcontract to Research Triangle Institute, Research Triangle Park, NC.

Environmental Protection Agency, 1978: Guideline on air quality models. EPA Report No. EPA-450/2-78-027, OAQPS No. 1.2-080, U. S. Environmental Protection Agency, Research Triangle Park, NC.

Fox, D. G., 1981: Judging air quality model performance: A summary of the AMS Workshop on Dispersion Model Performance. Bulletin American Meteorological Society, 62(5), 599-609.

REFERENCES (Continued)

Hanna, S., _et al._, 1982: Diffusion model development and evaluation and emission limitations at the Westvaco Luke Mill. _Document PA439_, Environmental Research & Technology, Inc., Concord, MA.

Londergan, R. J., _et al._, 1982: Evaluation of rural air quality simulation models. _TRC Project 1713-R80_ prepared for U. S. Environmental Protection Agency, Research Triangle Park, NC.

APPENDIX B

ANALYSIS OF OBSERVED HOURLY SO_2 CONCENTRATIONS

This appendix presents the results of the H. E. Cramer Company's analysis of the observed hourly SO_2 concentrations reported by Environmental Research & Technology, Inc. (ERT) to the U. S. Environmental Protection Agency (EPA) Region III for the second year of the Westvaco monitoring program. The 25 highest short-term (1-hour, 3-hour and 24-hour average) observed (minus background) concentrations at Monitors 1, 3, 4, 5, 6, 7, 8, 9 and 10 are listed in Tables B-1 through B-9. See Appendix A for a discussion of the procedures used to calculate hourly background concentrations (concentrations attributable to emissions from sources other than the Westvaco Main Stack). The observed (with background) and observed (minus background) annual average SO_2 concentrations at the nine monitors of concern for the model evaluation are given in Table B-10. Based on Tables B-1 through B-9, the 25 highest 1-hour, 3-hour and 24-hour average observed (minus background) SO_2 concentrations at all of the nine monitors of concern are respectively given in Tables B-11, B-12 and B-13.

TABLE B-1

TWENTY-FIVE HIGHEST OBSERVED (MINUS BACKGROUND) SHORT-TERM SO_2 CONCENTRATIONS AT MONITOR 1 DURING THE SECOND YEAR OF THE WESTVACO MONITORING PROGRAM

Rank	1-Hour Average Concentrations		3-Hour Average Concentrations		24-Hour Average Concentrations	
	Date (Hour)	Concentration (ppm)	Date (Period)	Concentration (ppm)	Date	Concentration (ppm)
01	22 Oct 81 (07)	0.7285	22 Oct 81 (3)	0.5412	13 Jan 81	0.1666
02	13 Jan 81 (04)	0.7160	19 Nov 81 (3)	0.5158	29 Dec 80	0.1375
03	13 Jan 81 (02)	0.6835	13 Jan 81 (1)	0.4620	09 Nov 81	0.1330
04	19 Nov 81 (08)	0.6780	13 Jan 81 (2)	0.4612	22 Oct 81	0.1113
05	13 Jan 81 (03)	0.6130	06 Jul 81 (7)	0.3768	05 Dec 80	0.0974
06	22 Oct 81 (08)	0.6085	09 Nov 81 (2)	0.3528	19 Nov 81	0.0863
07	21 Oct 81 (09)	0.5535	12 Nov 81 (8)	0.3125	04 Dec 80	0.0849
08	03 Apr 81 (08)	0.5155	08 Feb 81 (1)	0.3082	06 Jul 81	0.0847
09	08 Apr 81 (06)	0.5095	09 Nov 81 (3)	0.3065	03 Apr 81	0.0779
10	06 Jul 81 (20)	0.5065	05 Dec 80 (8)	0.2992	21 Aug 81	0.0681
11	08 Feb 81 (01)	0.4955	08 Apr 81 (3)	0.2982	08 Feb 81	0.0665
12	09 Nov 81 (06)	0.4935	25 Jan 81 (3)	0.2890	07 May 81	0.0661
13	19 Nov 81 (09)	0.4760	09 Nov 81 (1)	0.2850	12 Nov 81	0.0605
14	16 Feb 81 (01)	0.4535	22 Apr 81 (3)	0.2675	25 Jan 81	0.0589
15	26 Nov 81 (24)	0.4485	03 Apr 81 (3)	0.2672	19 Feb 81	0.0565
16	08 Apr 81 (08)	0.4455	08 Apr 81 (2)	0.2655	26 Feb 81	0.0558
17	25 Jan 81 (08)	0.4410	19 Feb 81 (4)	0.2460	26 Nov 81	0.0537
18	13 Jan 81 (05)	0.4355	21 Aug 81 (3)	0.2385	20 Oct 81	0.0524
19	19 Feb 81 (09)	0.4355	13 Jan 81 (3)	0.2380	16 Feb 81	0.0516
20	21 Aug 81 (08)	0.4345	21 Oct 81 (3)	0.2298	21 Oct 81	0.0505
21	04 Nov 81 (11)	0.4240	03 Apr 81 (2)	0.2135	14 Feb 81	0.0494
22	09 Nov 81 (08)	0.4135	29 Dec 80 (1)	0.2117	26 Sep 81	0.0483
23	05 Oct 81 (03)	0.4115	07 May 81 (2)	0.2088	12 Jun 81	0.0481
24	27 Nov 81 (01)	0.4090	29 Dec 80 (4)	0.2070	18 Aug 81	0.0469
25	04 Dec 81 (04)	0.4090	27 Nov 81 (1)	0.2045	16 Dec 80	0.0467

TABLE B-2

TWENTY-FIVE HIGHEST OBSERVED (MINUS BACKGROUND) SHORT-TERM SO_2 CONCENTRATIONS AT MONITOR 3 DURING THE SECOND YEAR OF THE WESTVACO MONITORING PROGRAM

Rank	1-Hour Average Concentrations		3-Hour Average Concentrations		24-Hour Average Concentrations	
	Date (Hour)	Concentration (ppm)	Date (Period)	Concentration (ppm)	Date	Concentration (ppm)
01	13 Jan 81 (02)	0.6475	13 Jan 81 (1)	0.4337	06 Jan 81	0.1585
02	13 Jan 81 (03)	0.6110	22 Oct 81 (3)	0.3842	13 Jan 81	0.1309
03	22 Oct 81 (08)	0.5735	19 Nov 81 (3)	0.3478	13 Nov 81	0.1083
04	19 Nov 81 (09)	0.5580	13 Jan 81 (2)	0.3085	29 Dec 80	0.0968
05	13 Nov 81 (21)	0.5375	06 Jan 81 (2)	0.2890	14 Nov 81	0.0906
06	06 Jan 81 (04)	0.5300	20 Oct 81 (8)	0.2775	09 Nov 81	0.0884
07	06 Jan 81 (03)	0.4855	06 Jan 81 (1)	0.2702	22 Oct 81	0.0787
08	20 Oct 81 (24)	0.4735	13 Nov 81 (7)	0.2575	19 Nov 81	0.0681
09	03 Apr 81 (08)	0.4705	06 Jan 81 (8)	0.2490	21 Aug 81	0.0623
10	22 Oct 81 (07)	0.4665	09 Nov 81 (2)	0.2302	20 Oct 81	0.0539
11	26 Aug 81 (09)	0.4555	01 Apr 81 (4)	0.2297	14 Feb 81	0.0533
12	13 Jan 81 (04)	0.4150	09 Nov 81 (1)	0.2288	07 May 81	0.0498
13	01 Apr 81 (11)	0.3895	08 Apr 81 (3)	0.2122	11 Apr 81	0.0495
14	08 Feb 81 (01)	0.3855	11 Apr 81 (2)	0.2105	24 Mar 81	0.0480
15	19 Nov 81 (08)	0.3810	08 Feb 81 (1)	0.2068	03 Apr 81	0.0471
16	09 Nov 81 (02)	0.3725	14 Nov 81 (4)	0.2038	26 Nov 81	0.0468
17	14 Feb 81 (21)	0.3660	22 Apr 81 (3)	0.1945	22 Apr 81	0.0421
18	14 Nov 81 (12)	0.3655	06 Jan 81 (5)	0.1858	15 Oct 81	0.0407
19	11 Apr 81 (04)	0.3595	12 Nov 81 (8)	0.1858	12 Jun 81	0.0403
20	12 Jun 81 (08)	0.3575	21 Aug 81 (3)	0.1848	19 Feb 81	0.0401
21	18 Aug 81 (09)	0.3535	14 Nov 81 (2)	0.1818	18 Aug 81	0.0397
22	26 Nov 81 (24)	0.3505	13 Nov 81 (2)	0.1815	23 Dec 80	0.0392
23	04 Nov 81 (11)	0.3450	27 Nov 81 (1)	0.1778	08 Feb 81	0.0378
24	28 Jun 81 (09)	0.3415	03 Apr 81 (3)	0.1758	21 Oct 81	0.0375
25	20 Oct 81 (23)	0.3345	26 Aug 81 (3)	0.1722	01 Apr 81	0.0375

TABLE B-3

TWENTY-FIVE HIGHEST OBSERVED (MINUS BACKGROUND) SHORT-TERM SO_2 CONCENTRATIONS AT MONITOR 4 DURING THE SECOND YEAR OF THE WESTVACO MONITORING PROGRAM

Rank	1-Hour Average Concentrations		3-Hour Average Concentrations		24-Hour Average Concentrations	
	Date (Hour)	Concentration (ppm)	Date (Period)	Concentration (ppm)	Date	Concentration (ppm)
01	13 Jan 81 (03)	0.8740	13 Jan 81 (1)	0.4560	13 Jan 81	0.1419
02	19 Feb 81 (10)	0.6255	19 Feb 81 (4)	0.3733	06 Jan 81	0.1147
03	06 Jan 81 (03)	0.5215	13 Jan 81 (2)	0.3528	13 Nov 81	0.1097
04	22 Apr 81 (08)	0.5080	22 Oct 81 (3)	0.3165	14 Nov 81	0.0805
05	13 Jan 81 (02)	0.4795	06 Jan 81 (1)	0.3005	21 Aug 81	0.0787
06	13 Jan 81 (05)	0.4775	22 Apr 81 (3)	0.2775	19 Feb 81	0.0703
07	14 Feb 81 (21)	0.4510	12 Nov 81 (8)	0.2722	22 Apr 81	0.0574
08	19 Feb 81 (11)	0.4415	06 Jan 81 (8)	0.2687	04 Dec 80	0.0571
09	13 Nov 81 (04)	0.4285	13 Nov 81 (2)	0.2675	14 Feb 81	0.0568
10	06 Jan 81 (23)	0.4125	21 Aug 81 (3)	0.2348	26 Nov 81	0.0511
11	12 Jun 81 (08)	0.4035	13 Nov 81 (1)	0.2318	22 Oct 81	0.0508
12	14 Nov 81 (12)	0.3905	14 Nov 81 (4)	0.2275	24 Mar 81	0.0498
13	22 Oct 81 (08)	0.3895	08 Feb 81 (1)	0.2158	07 May 81	0.0482
14	22 Oct 81 (07)	0.3845	14 Feb 81 (7)	0.2138	12 Nov 81	0.0472
15	12 Nov 81 (23)	0.3615	04 Dec 80 (8)	0.2032	16 Feb 81	0.0457
16	21 Aug 81 (04)	0.3385	21 Aug 81 (1)	0.2015	18 Aug 81	0.0423
17	19 Feb 81 (09)	0.3375	13 Jan 81 (3)	0.1850	08 Feb 81	0.0418
18	13 Jan 81 (04)	0.3340	12 Jun 81 (3)	0.1845	05 Dec 80	0.0418
19	13 Nov 81 (01)	0.3235	16 Feb 81 (1)	0.1768	18 Mar 81	0.0355
20	19 Jun 81 (09)	0.3075	08 May 81 (1)	0.1708	27 Dec 80	0.0350
21	21 Aug 81 (02)	0.3075	15 Oct 81 (1)	0.1688	27 Feb 81	0.0347
22	15 Oct 81 (02)	0.3055	20 Oct 81 (8)	0.1665	26 Sep 81	0.0347
23	21 Aug 81 (08)	0.3045	21 Aug 81 (2)	0.1658	25 Jan 81	0.0344
24	06 Jan 81 (02)	0.3015	13 Nov 81 (3)	0.1658	04 May 81	0.0343
25	08 Feb 81 (01)	0.3015	01 Apr 81 (4)	0.1587	15 Oct 81	0.0339

TABLE B-4

TWENTY-FIVE HIGHEST OBSERVED (MINUS BACKGROUND) SHORT-TERM SO_2 CONCENTRATIONS AT MONITOR 5 DURING THE SECOND YEAR OF THE WESTVACO MONITORING PROGRAM

Rank	1-Hour Average Concentrations		3-Hour Average Concentrations		24-Hour Average Concentrations	
	Date (Hour)	Concentration (ppm)	Date (Period)	Concentration (ppm)	Date	Concentration (ppm)
01	21 Aug 81 (03)	0.8935	13 Nov 81 (2)	0.6235	13 Nov 81	0.1546
02	27 Nov 81 (01)	0.7750	21 Aug 81 (1)	0.4518	29 Dec 80	0.1015
03	13 Nov 81 (02)	0.7625	16 Feb 81 (1)	0.4062	16 Feb 81	0.0828
04	13 Nov 81 (05)	0.7585	21 Sep 81 (1)	0.4038	13 Jan 81	0.0816
05	13 Nov 81 (06)	0.7145	22 Apr 81 (3)	0.3902	21 Aug 81	0.0813
06	13 Jan 81 (03)	0.6550	14 Feb 81 (8)	0.3597	01 May 81	0.0812
07	25 Jan 81 (24)	0.6515	13 Nov 81 (1)	0.2975	22 Apr 81	0.0760
08	21 Sep 81 (02)	0.6365	04 Dec 80 (7)	0.2743	14 Feb 81	0.0742
09	29 Dec 80 (01)	0.5970	27 Nov 81 (1)	0.2665	21 Sep 81	0.0684
10	14 Feb 81 (22)	0.5770	29 Dec 80 (1)	0.2577	17 Aug 81	0.0647
11	22 Apr 81 (07)	0.5265	25 Jan 81 (8)	0.2538	04 Dec 80	0.0608
12	21 Sep 81 (03)	0.4945	01 May 81 (1)	0.2382	24 Mar 81	0.0607
13	16 Feb 81 (01)	0.4875	26 Sep 81 (2)	0.2375	26 Nov 81	0.0522
14	01 May 81 (04)	0.4735	01 May 81 (2)	0.2252	22 Dec 80	0.0510
15	04 Dec 80 (20)	0.4430	22 Dec 80 (2)	0.2233	26 Sep 81	0.0499
16	17 Jul 81 (21)	0.4415	13 Jan 81 (1)	0.2227	17 Jul 81	0.0494
17	16 Feb 81 (02)	0.4335	16 Dec 80 (3)	0.2190	25 Jan 81	0.0471
18	21 Aug 81 (02)	0.4305	06 Feb 81 (1)	0.2095	14 Nov 81	0.0448
19	22 Apr 81 (08)	0.4130	24 Mar 81 (2)	0.1975	16 Dec 80	0.0425
20	26 Sep 81 (06)	0.4035	29 Dec 80 (6)	0.1863	20 May 81	0.0400
21	13 Nov 81 (04)	0.3975	26 Nov 81 (1)	0.1773	19 Feb 81	0.0391
22	20 May 81 (08)	0.3835	13 Jan 81 (4)	0.1717	06 Jan 81	0.0379
23	08 Apr 81 (05)	0.3725	05 Aug 81 (8)	0.1662	09 Jan 81	0.0374
24	01 May 81 (03)	0.3685	12 Jun 81 (3)	0.1582	08 Apr 81	0.0364
25	26 Nov 81 (01)	0.3680	29 Dec 80 (3)	0.1578	27 Nov 81	0.0356

TABLE B-5

TWENTY-FIVE HIGHEST OBSERVED (MINUS BACKGROUND) SHORT-TERM SO_2 CONCENTRATIONS AT MONITOR 6 DURING THE SECOND YEAR OF THE WESTVACO MONITORING PROGRAM

Rank	1-Hour Average Concentrations		3-Hour Average Concentrations		24-Hour Average Concentrations	
	Date (Hour)	Concentration (ppm)	Date (Period)	Concentration (ppm)	Date	Concentration (ppm)
01	13 Jan 81 (04)	0.8660	08 Apr 81 (3)	0.6142	08 Apr 81	0.1501
02	19 Nov 81 (09)	0.8250	08 Apr 81 (2)	0.5268	13 Jan 81	0.1432
03	08 Apr 81 (07)	0.8165	13 Jan 81 (2)	0.5135	05 Dec 80	0.1299
04	08 Apr 81 (08)	0.7825	29 Mar 81 (2)	0.4435	13 Nov 81	0.1274
05	08 Apr 81 (06)	0.7585	19 Nov 81 (3)	0.4228	17 Jan 81	0.1257
06	16 Feb 81 (01)	0.7125	13 Nov 81 (7)	0.3648	02 Jan 81	0.1232
07	08 Apr 81 (05)	0.6915	04 Nov 81 (4)	0.3382	14 Nov 81	0.1219
08	04 Nov 81 (11)	0.6670	03 Apr 81 (2)	0.3332	29 Dec 80	0.1195
09	13 Nov 81 (21)	0.6325	19 Nov 81 (4)	0.3048	03 Apr 81	0.1191
10	05 Dec 80 (17)	0.5910	03 Apr 81 (3)	0.2978	14 Dec 80	0.1144
11	29 Mar 81 (04)	0.5545	27 Nov 81 (1)	0.2942	19 Nov 81	0.1082
12	05 Nov 81 (11)	0.4865	05 Dec 80 (6)	0.2938	07 Oct 81	0.1035
13	27 Nov 81 (01)	0.4730	05 Dec 80 (7)	0.2752	28 Nov 81	0.0983
14	15 Feb 81 (09)	0.4635	05 Dec 80 (8)	0.2715	16 Feb 81	0.0945
15	19 Nov 81 (10)	0.4510	16 Feb 81 (1)	0.2672	27 Nov 81	0.0897
16	19 Nov 81 (11)	0.4445	17 Jan 81 (7)	0.2542	13 Dec 80	0.0883
17	03 Apr 81 (05)	0.4415	15 Feb 81 (3)	0.2528	10 Dec 80	0.0862
18	26 Nov 81 (24)	0.4395	13 Jan 81 (1)	0.2473	28 Feb 81	0.0853
19	29 Mar 81 (05)	0.4365	28 Feb 81 (4)	0.2455	29 Nov 81	0.0831
20	28 Feb 81 (10)	0.4285	14 Nov 81 (4)	0.2412	17 Nov 81	0.0817
21	05 Dec 80 (24)	0.4245	09 Dec 80 (7)	0.2375	04 Dec 80	0.0799
22	13 Jan 81 (05)	0.4215	13 Jan 81 (3)	0.2203	12 Nov 81	0.0786
23	14 Feb 81 (21)	0.4210	04 Dec 80 (4)	0.2132	18 Nov 81	0.0774
24	13 Nov 81 (20)	0.4125	05 Nov 81 (4)	0.2127	16 May 81	0.0752
25	24 May 81 (02)	0.3970	02 Dec 80 (2)	0.2122	20 Mar 81	0.0746

TABLE B-6

TWENTY-FIVE HIGHEST OBSERVED (MINUS BACKGROUND) SHORT-TERM SO_2 CONCENTRATIONS AT MONITOR 7 DURING THE SECOND YEAR OF THE WESTVACO MONITORING PROGRAM

Rank	1-Hour Average Concentrations		3-Hour Average Concentrations		24-Hour Average Concentrations	
	Date (Hour)	Concentration (ppm)	Date (Period)	Concentration (ppm)	Date	Concentration (ppm)
01	13 Nov 81 (05)	0.8525	13 Nov 81 (2)	0.7432	29 Dec 80	0.0994
02	13 Nov 81 (02)	0.8475	13 Nov 81 (1)	0.6575	22 Apr 81	0.0947
03	13 Nov 81 (06)	0.7525	16 Feb 81 (1)	0.3748	12 Nov 81	0.0707
04	13 Nov 81 (01)	0.6685	22 Apr 81 (3)	0.3712	26 Sep 81	0.0688
05	29 Dec 80 (01)	0.6380	18 Aug 81 (8)	0.3578	01 May 81	0.0686
06	08 Feb 81 (01)	0.6355	08 Feb 81 (1)	0.3362	16 Feb 81	0.0666
07	13 Nov 81 (04)	0.6245	12 Nov 81 (8)	0.3258	14 Feb 81	0.0626
08	16 Feb 81 (01)	0.6035	06 Jan 81 (8)	0.2690	18 Aug 81	0.0617
09	25 Jan 81 (24)	0.5935	20 Aug 81 (8)	0.2605	04 Dec 80	0.0589
10	20 Aug 81 (24)	0.5705	29 Dec 80 (1)	0.2600	20 Aug 81	0.0571
11	09 Jan 81 (04)	0.5070	01 May 81 (2)	0.2598	13 Jan 81	0.0556
12	07 Feb 81 (24)	0.5040	26 Sep 81 (2)	0.2588	30 Sep 81	0.0526
13	18 Aug 81 (23)	0.4915	22 Apr 81 (2)	0.2525	08 Feb 81	0.0505
14	18 Oct 81 (05)	0.4875	14 Feb 81 (8)	0.2340	09 Jan 81	0.0501
15	01 May 81 (04)	0.4855	16 Dec 80 (3)	0.2320	17 Jul 81	0.0477
16	13 Mar 81 (03)	0.4565	25 Jan 81 (8)	0.2248	06 Jan 81	0.0475
17	20 May 81 (08)	0.4415	19 Aug 81 (2)	0.2165	07 May 81	0.0461
18	22 Apr 81 (08)	0.4390	22 Mar 81 (3)	0.2058	19 Aug 81	0.0458
19	26 Sep 81 (06)	0.4385	14 May 81 (3)	0.2017	24 Mar 81	0.0444
20	22 Apr 81 (07)	0.4325	09 Jan 81 (2)	0.1987	28 Dec 80	0.0442
21	14 May 81 (08)	0.4305	07 Feb 81 (8)	0.1947	20 May 81	0.0438
22	17 Jul 81 (21)	0.4285	21 Mar 81 (8)	0.1892	18 Oct 81	0.0420
23	12 Nov 81 (23)	0.4145	08 May 81 (1)	0.1868	22 Mar 81	0.0419
24	18 Aug 81 (22)	0.4135	04 Dec 80 (7)	0.1867	17 Aug 81	0.0414
25	13 Jan 81 (03)	0.4110	04 Dec 80 (8)	0.1852	16 Dec 80	0.0406

TABLE B-7

TWENTY-FIVE HIGHEST OBSERVED (MINUS BACKGROUND) SHORT-TERM SO_2 CONCENTRATIONS AT MONITOR 8 DURING THE SECOND YEAR OF THE WESTVACO MONITORING PROGRAM

Rank	1-Hour Average Concentrations		3-Hour Average Concentrations		24-Hour Average Concentrations	
	Date (Hour)	Concentration (ppm)	Date (Period)	Concentration (ppm)	Date	Concentration (ppm)
01	13 Nov 81 (02)	0.8435	13 Nov 81 (2)	0.5195	13 Nov 81	0.1255
02	13 Nov 81 (05)	0.8215	13 Nov 81 (1)	0.3325	01 May 81	0.0820
03	27 Nov 81 (01)	0.8070	01 May 81 (2)	0.3012	29 Dec 80	0.0752
04	20 Aug 81 (24)	0.6695	21 Sep 81 (1)	0.2772	22 Apr 81	0.0656
05	21 Sep 81 (02)	0.5185	04 Dec 80 (7)	0.2743	26 Nov 81	0.0640
06	04 Dec 80 (21)	0.4910	01 May 81 (1)	0.2722	04 Dec 80	0.0639
07	01 May 81 (04)	0.4565	27 Nov 81 (1)	0.2702	30 Sep 81	0.0591
08	13 Nov 81 (04)	0.4195	20 Aug 81 (8)	0.2682	20 Aug 81	0.0540
09	14 Nov 81 (13)	0.4135	22 Apr 81 (3)	0.2625	28 Dec 80	0.0525
10	08 May 81 (01)	0.3945	21 Mar 81 (8)	0.1938	21 Sep 81	0.0509
11	28 Dec 80 (19)	0.3705	22 Apr 81 (2)	0.1905	14 Feb 81	0.0504
12	29 Dec 80 (09)	0.3640	29 Dec 80 (3)	0.1882	13 Jan 81	0.0463
13	01 May 81 (01)	0.3525	28 Dec 80 (7)	0.1848	20 May 81	0.0462
14	22 Apr 81 (08)	0.3410	14 Feb 81 (8)	0.1713	09 Jan 81	0.0435
15	01 May 81 (05)	0.3225	14 Nov 81 (5)	0.1695	27 Nov 81	0.0431
16	30 Sep 81 (09)	0.3220	30 Sep 81 (3)	0.1677	18 Oct 81	0.0400
17	14 Feb 81 (21)	0.3210	06 Feb 81 (1)	0.1605	14 Nov 81	0.0396
18	13 Nov 81 (06)	0.3175	19 Aug 81 (2)	0.1525	23 Nov 81	0.0346
19	04 Dec 80 (20)	0.3150	24 Nov 81 (1)	0.1398	06 Jan 81	0.0345
20	21 Sep 81 (03)	0.3105	13 Jan 81 (4)	0.1397	22 Dec 80	0.0338
21	13 Jan 81 (12)	0.3070	29 Dec 80 (4)	0.1377	19 Aug 81	0.0314
22	09 Jan 81 (04)	0.3060	04 Dec 80 (8)	0.1372	24 Mar 81	0.0310
23	03 Nov 81 (08)	0.3045	20 Aug 81 (1)	0.1362	12 Nov 81	0.0304
24	18 Oct 81 (05)	0.3015	08 May 81 (1)	0.1332	05 Dec 80	0.0303
25	29 Dec 80 (10)	0.2970	09 Jan 81 (2)	0.1297	24 Nov 81	0.0298

TABLE B-8

TWENTY-FIVE HIGHEST OBSERVED (MINUS BACKGROUND) SHORT-TERM SO_2 CONCENTRATIONS AT MONITOR 9 DURING THE SECOND YEAR OF THE WESTVACO MONITORING PROGRAM

Rank	1-Hour Average Concentrations		3-Hour Average Concentrations		24-Hour Average Concentrations	
	Date (Hour)	Concentration (ppm)	Date (Period)	Concentration (ppm)	Date	Concentration (ppm)
01	21 Aug 81 (03)	0.7095	13 Nov 81 (2)	0.4728	01 May 81	0.1099
02	13 Nov 81 (05)	0.6225	01 May 81 (1)	0.4008	13 Nov 81	0.1070
03	16 Feb 81 (02)	0.6185	01 May 81 (2)	0.3832	14 Feb 81	0.0699
04	01 May 81 (01)	0.6095	22 Apr 81 (3)	0.3612	22 Apr 81	0.0679
05	01 May 81 (04)	0.6035	14 Feb 81 (8)	0.3557	26 Nov 81	0.0607
06	29 Dec 80 (09)	0.5900	21 Sep 81 (1)	0.3198	29 Dec 80	0.0588
07	27 Nov 81 (01)	0.5580	16 Feb 81 (1)	0.2685	16 Feb 81	0.0551
08	21 Sep 81 (02)	0.5485	21 Aug 81 (1)	0.2575	30 Sep 81	0.0532
09	22 Apr 81 (07)	0.5325	08 Feb 81 (1)	0.2188	19 Aug 81	0.0530
10	14 Feb 81 (22)	0.4930	29 Dec 80 (3)	0.2185	21 Sep 81	0.0511
11	13 Nov 81 (06)	0.4835	19 Aug 81 (2)	0.2162	09 Jan 81	0.0460
12	08 Feb 81 (01)	0.4685	04 Dec 80 (7)	0.2000	24 Mar 81	0.0450
13	13 Nov 81 (02)	0.4275	18 Aug 81 (8)	0.1902	04 Dec 80	0.0439
14	18 Oct 81 (05)	0.4235	27 Nov 81 (1)	0.1885	07 May 81	0.0428
15	21 Sep 81 (03)	0.4085	24 Mar 81 (2)	0.1532	22 Dec 80	0.0422
16	01 May 81 (05)	0.3965	22 Dec 80 (2)	0.1490	17 Aug 81	0.0417
17	07 May 81 (24)	0.3965	14 Nov 81 (5)	0.1482	14 Nov 81	0.0415
18	14 Feb 81 (23)	0.3810	30 Sep 81 (3)	0.1453	08 Feb 81	0.0408
19	13 Jan 81 (12)	0.3680	13 Nov 81 (1)	0.1442	21 Aug 81	0.0405
20	22 Apr 81 (06)	0.3645	13 Jan 81 (4)	0.1427	20 May 81	0.0395
21	01 May 81 (03)	0.3515	21 Mar 81 (8)	0.1375	17 Jul 81	0.0368
22	22 Apr 81 (08)	0.3430	07 May 81 (8)	0.1375	27 Nov 81	0.0351
23	17 Jul 81 (21)	0.3295	03 Nov 81 (3)	0.1363	23 Nov 81	0.0313
24	04 Dec 80 (21)	0.3190	26 Sep 81 (2)	0.1325	18 Oct 81	0.0297
25	18 Aug 81 (23)	0.3155	23 Nov 81 (8)	0.1278	13 Jan 81	0.0284

TABLE B-9

TWENTY-FIVE HIGHEST OBSERVED (MINUS BACKGROUND) SHORT-TERM SO_2 CONCENTRATIONS AT MONITOR 10 DURING THE SECOND YEAR OF THE WESTVACO MONITORING PROGRAM

Rank	1-Hour Average Concentrations		3-Hour Average Concentrations		24-Hour Average Concentrations	
	Date (Hour)	Concentration (ppm)	Date (Period)	Concentration (ppm)	Date	Concentration (ppm)
01	06 Feb 81 (09)	0.2105	06 Jan 81 (4)	0.1592	09 Jan 81	0.0433
02	06 Jan 81 (10)	0.2055	09 Jan 81 (4)	0.1120	03 Jan 81	0.0373
03	15 Aug 81 (10)	0.2055	18 Jun 81 (3)	0.1078	06 Jan 81	0.0354
04	08 Jun 81 (23)	0.1785	15 Aug 81 (4)	0.1028	12 Dec 80	0.0316
05	06 Jan 81 (11)	0.1765	06 Feb 81 (3)	0.0992	23 Dec 80	0.0315
06	18 Jun 81 (08)	0.1685	03 Jan 81 (4)	0.0863	13 Jan 81	0.0294
07	23 Apr 81 (10)	0.1615	05 Jul 81 (4)	0.0855	22 Dec 80	0.0291
08	06 Oct 81 (06)	0.1595	09 Jan 81 (3)	0.0850	29 Dec 80	0.0273
09	09 Jan 81 (10)	0.1560	23 Dec 80 (2)	0.0785	15 Aug 81	0.0271
10	09 Jan 81 (11)	0.1370	03 Jan 81 (2)	0.0770	05 Jan 81	0.0263
11	15 Aug 81 (09)	0.1305	08 Jun 81 (8)	0.0752	08 Jan 81	0.0219
12	09 Jan 81 (09)	0.1290	13 Jan 81 (3)	0.0707	05 Jul 81	0.0206
13	18 Jun 81 (07)	0.1225	22 Dec 80 (3)	0.0692	06 Feb 81	0.0204
14	08 Apr 81 (09)	0.1205	23 Dec 80 (3)	0.0685	24 Nov 81	0.0200
15	20 Jul 81 (10)	0.1155	13 Jan 81 (2)	0.0652	26 Nov 81	0.0200
16	21 Jun 81 (08)	0.1125	23 Apr 81 (4)	0.0652	16 Dec 80	0.0198
17	11 Mar 81 (05)	0.1095	12 Dec 80 (4)	0.0647	30 Sep 81	0.0188
18	30 Sep 81 (13)	0.1090	11 Mar 81 (2)	0.0628	13 Feb 81	0.0184
19	25 Sep 81 (10)	0.1075	21 Jun 81 (3)	0.0618	05 Feb 81	0.0182
20	05 Jul 81 (11)	0.1055	06 Oct 81 (2)	0.0618	03 Nov 81	0.0180
21	30 May 81 (09)	0.1025	08 Jan 81 (8)	0.0608	06 Oct 81	0.0173
22	13 Jan 81 (10)	0.1010	12 Dec 80 (6)	0.0585	25 Dec 80	0.0173
23	03 Jan 81 (11)	0.1000	07 Jan 81 (8)	0.0583	01 Jan 81	0.0172
24	30 May 81 (10)	0.0975	29 Sep 81 (4)	0.0560	18 Jun 81	0.0170
25	23 Dec 80 (05)	0.0965	10 Aug 81 (4)	0.0547	14 Jun 81	0.0168

TABLE B-10

OBSERVED ANNUAL AVERAGE SO_2 CONCENTRATIONS DURING THE SECOND YEAR OF THE WESTVACO MONITORING PROGRAM

Site	No. of Hours of Valid Data	Annual Average Concentration (ppm)	
		With Background	Without Background
1	7,807	0.026	0.022
3	6,628	0.023	0.018
4	7,828	0.019	0.014
5	7,977	0.019	0.014
6	7,123	0.039	0.034
7	7,939	0.019	0.014
8	8,209	0.017	0.012
9	8,291	0.016	0.011
10	8,507	0.012	0.008

TABLE B-11

TWENTY-FIVE HIGHEST OBSERVED (MINUS BACKGROUND) 1-HOUR SO_2 CONCENTRATIONS AT ALL MONITORS DURING THE SECOND YEAR OF THE WESTVACO MONITORING PROGRAM

Rank	Monitor	Date (Hour)	Concentration (ppm)
1	5	21 Aug 81 (03)	0.8935
2	4	13 Jan 81 (03)	0.8740
3	6	13 Jan 81 (04)	0.8660
4	7	13 Nov 81 (05)	0.8525
5	7	13 Nov 81 (02)	0.8475
6	8	13 Nov 81 (02)	0.8435
7	6	19 Nov 81 (09)	0.8250
8	8	13 Nov 81 (05)	0.8215
9	6	8 Apr 81 (07)	0.8165
10	8	27 Nov 81 (01)	0.8070
11	6	8 Apr 81 (08)	0.7825
12	5	27 Nov 81 (01)	0.7750
13	5	13 Nov 81 (02)	0.7625
14	5	13 Nov 81 (05)	0.7585
15	6	8 Apr 81 (06)	0.7585
16	7	13 Nov 81 (06)	0.7525
17	1	22 Oct 81 (07)	0.7285
18	1	13 Jan 81 (04)	0.7160
19	5	13 Nov 81 (06)	0.7145
20	6	16 Feb 81 (01)	0.7125
21	9	21 Aug 81 (03)	0.7095
22	6	8 Apr 81 (05)	0.6915
23	1	13 Jan 81 (02)	0.6835
24	1	19 Nov 81 (08)	0.6780
25	8	20 Aug 81 (24)	0.6695

TABLE B-12

TWENTY-FIVE HIGHEST OBSERVED (MINUS BACKGROUND) 3-HOUR SO_2 CONCENTRATIONS AT ALL MONITORS DURING THE SECOND YEAR OF THE WESTVACO MONITORING PROGRAM

Rank	Monitor	Date (Period)	Concentration (ppm)
1	7	13 Nov 81 (2)	0.7432
2	7	13 Nov 81 (1)	0.6575
3	5	13 Nov 81 (2)	0.6235
4	6	8 Apr 81 (3)	0.6142
5	1	22 Oct 81 (3)	0.5412
6	6	8 Apr 81 (2)	0.5268
7	8	13 Nov 81 (2)	0.5195
8	1	19 Nov 81 (3)	0.5158
9	6	13 Jan 81 (2)	0.5135
10	9	13 Nov 81 (2)	0.4728
11	1	13 Jan 81 (1)	0.4620
12	1	13 Jan 81 (2)	0.4612
13	4	13 Jan 81 (1)	0.4560
14	5	21 Aug 81 (1)	0.4518
15	6	29 Mar 81 (2)	0.4435
16	3	13 Jan 81 (1)	0.4337
17	6	19 Nov 81 (3)	0.4228
18	5	16 Feb 81 (1)	0.4062
19	5	21 Sep 81 (1)	0.4038
20	9	1 May 81 (1)	0.4008
21	5	22 Apr 81 (3)	0.3902
22	3	22 Oct 81 (3)	0.3842
23	9	1 May 81 (2)	0.3832
24	1	6 Jul 81 (7)	0.3768
25	7	16 Feb 81 (1)	0.3748

TABLE B-13

TWENTY-FIVE HIGHEST OBSERVED (MINUS BACKGROUND) 24-HOUR SO_2 CONCENTRATIONS AT ALL MONITORS DURING THE SECOND YEAR OF THE WESTVACO MONITORING PROGRAM

Rank	Monitor	Date	Concentration (ppm)
1	1	13 Jan 81	0.1666
2	3	6 Jan 81	0.1585
3	5	13 Nov 81	0.1546
4	6	8 Apr 81	0.1501
5	6	13 Jan 81	0.1432
6	4	13 Jan 81	0.1419
7	1	29 Dec 80	0.1375
8	1	9 Nov 81	0.1330
9	3	13 Jan 81	0.1309
10	6	5 Dec 80	0.1299
11	6	13 Nov 81	0.1274
12	6	17 Jan 81	0.1257
13	8	13 Nov 81	0.1255
14	6	2 Jan 81	0.1232
15	6	14 Nov 81	0.1219
16	6	29 Dec 80	0.1195
17	6	3 Apr 81	0.1191
18	4	6 Jan 81	0.1147
19	6	14 Dec 80	0.1144
20	1	22 Oct 81	0.1113
21	9	1 May 81	0.1099
22	4	13 Nov 81	0.1097
23	3	13 Nov 81	0.1083
24	6	19 Nov 81	0.1082
25	9	13 Nov 82	0.1070

APPENDIX C

RESULTS OF THE SHORTZ MODEL CONCENTRATION CALCULATIONS

This appendix presents the results of the SHORTZ model concentration calculations performed by the H. E. Cramer Company for the second year of the Westvaco Monitoring program. The 25 highest short-term (1-hour, 3-hour and 24-hour average) SO_2 concentrations calculated by the SHORTZ model at Monitors 1, 3, 4, 5, 6, 7, 8, 9 and 10 are listed in Tables C-1 through C-9. The annual average concentrations calculated at these nine monitors of concern for the model evaluation are shown in Table C-10. Based on Tables C-1 through C-9, the 25 highest 1-hour, 3-hour and 24-hour average SO_2 concentrations calculated by SHORTZ at all of the nine monitors of concern are respectively given in Tables C-11, C-12 and C-13.

TABLE C-1

TWENTY-FIVE HIGHEST SHORT-TERM SO_2 CONCENTRATIONS CALCULATED BY SHORTZ AT MONITOR 1 DURING THE SECOND YEAR OF THE WESTVACO MONITORING PROGRAM

Rank	1-Hour Average Concentrations		3-Hour Average Concentrations		24-Hour Average Concentrations	
	Date (Hour)	Concentration (ppm)	Date (Period)	Concentration (ppm)	Date	Concentration (ppm)
01	29 Dec 80 (10)	6.8795	18 May 81 (1)	3.1736	29 Dec 80	0.7163
02	26 Nov 81 (23)	5.8871	04 Nov 81 (7)	3.1540	08 Feb 81	0.6694
03	18 May 81 (02)	5.7255	29 Dec 80 (4)	2.5622	06 May 81	0.6067
04	04 Nov 81 (21)	5.4999	04 Dec 80 (7)	2.4438	23 May 81	0.5918
05	17 Feb 81 (21)	4.7498	23 May 81 (1)	2.3912	18 May 81	0.5175
06	12 Feb 81 (22)	4.5901	08 Feb 81 (1)	2.3584	07 Jun 81	0.5140
07	04 Dec 80 (21)	4.5057	02 May 81 (8)	2.3532	03 Aug 81	0.4894
08	02 May 81 (23)	4.2689	29 Dec 80 (7)	2.2477	02 May 81	0.4723
09	03 May 81 (24)	4.2618	30 Nov 81 (2)	1.9947	03 May 81	0.4594
10	04 May 81 (23)	4.0195	26 Nov 81 (8)	1.9624	04 Nov 81	0.4376
11	22 May 81 (24)	3.9969	14 Nov 81 (8)	1.9163	12 Nov 81	0.4281
12	04 Nov 81 (20)	3.9622	06 May 81 (2)	1.7978	25 Mar 81	0.4162
13	30 Nov 81 (05)	3.9147	06 May 81 (1)	1.7698	15 Jul 81	0.4121
14	22 Apr 81 (06)	3.7116	22 May 81 (8)	1.7091	22 May 81	0.3963
15	08 Feb 81 (08)	3.7042	17 Feb 81 (7)	1.6019	12 Feb 81	0.3939
16	18 May 81 (03)	3.6565	08 Feb 81 (3)	1.5866	30 Nov 81	0.3844
17	23 May 81 (05)	3.6200	23 May 81 (2)	1.5711	17 Aug 81	0.3655
18	29 Dec 80 (21)	3.5932	07 Jun 81 (2)	1.5549	11 Jun 81	0.3542
19	23 May 81 (02)	3.5367	12 Feb 81 (8)	1.5300	27 Jul 81	0.3412
20	05 May 81 (01)	3.5339	03 May 81 (8)	1.5082	04 Dec 80	0.3319
21	06 May 81 (02)	3.4979	12 Nov 81 (2)	1.4801	30 Dec 80	0.3117
22	08 Feb 81 (02)	3.4590	15 Jul 81 (7)	1.4701	08 Jan 81	0.3012
23	10 Apr 81 (03)	3.3584	27 Jul 81 (7)	1.4660	14 Nov 81	0.2928
24	25 Mar 81 (21)	3.3150	25 Mar 81 (7)	1.4243	26 Apr 81	0.2811
25	08 Aug 81 (01)	3.2281	08 Jan 81 (7)	1.4229	29 Jul 81	0.2761

TABLE C-2

TWENTY-FIVE HIGHEST SHORT-TERM SO_2 CONCENTRATIONS CALCULATED BY SHORTZ AT MONITOR 3 DURING THE SECOND YEAR OF THE WESTVACO MONITORING PROGRAM

Rank	1-Hour Average Concentrations		3-Hour Average Concentrations		24-Hour Average Concentrations	
	Date (Hour)	Concentration (ppm)	Date (Period)	Concentration (ppm)	Date	Concentration (ppm)
01	03 May 81 (23)	6.5644	23 May 81 (2)	4.1034	23 May 81	0.8503
02	23 May 81 (04)	6.5305	23 May 81 (1)	2.5276	03 May 81	0.6660
03	23 May 81 (03)	5.8840	03 May 81 (8)	2.3627	17 Aug 81	0.4989
04	23 May 81 (05)	5.7796	03 May 81 (1)	2.1184	10 Jul 81	0.3647
05	18 Jun 81 (01)	4.0196	25 Aug 81 (1)	1.9888	15 Jul 81	0.3524
06	27 Aug 81 (21)	3.5355	01 Jun 81 (1)	1.9689	25 Aug 81	0.3380
07	17 May 81 (24)	3.5058	27 Aug 81 (7)	1.9673	17 May 81	0.2666
08	03 May 81 (01)	3.3168	10 Jul 81 (8)	1.7685	01 Jun 81	0.2535
09	08 Jan 81 (22)	3.2510	17 May 81 (8)	1.6580	27 Aug 81	0.2495
10	01 Jun 81 (02)	3.2469	18 Jun 81 (1)	1.3399	17 Jun 81	0.2387
11	25 Aug 81 (02)	2.9568	17 Jun 81 (8)	1.3068	02 May 81	0.2337
12	24 May 81 (04)	2.8205	17 Aug 81 (7)	1.3021	22 Jul 81	0.2157
13	17 Aug 81 (21)	2.7610	17 Aug 81 (2)	1.2940	26 Jun 81	0.2040
14	10 Apr 81 (02)	2.7427	04 Dec 80 (7)	1.2490	06 May 81	0.1987
15	01 Jun 81 (01)	2.6599	20 May 81 (1)	1.1868	14 Nov 81	0.1985
16	17 Jun 81 (24)	2.6310	10 Apr 81 (1)	1.1131	24 Mar 81	0.1831
17	17 Aug 81 (04)	2.6016	08 Jan 81 (8)	1.0837	20 May 81	0.1732
18	30 Jul 81 (01)	2.5970	22 Jul 81 (8)	0.9610	30 Jul 81	0.1726
19	03 May 81 (02)	2.5478	02 May 81 (8)	0.9484	18 Jun 81	0.1675
20	31 Jul 81 (04)	2.3634	27 Jun 81 (1)	0.9439	18 Jul 81	0.1660
21	15 Jul 81 (22)	2.3499	24 May 81 (2)	0.9402	04 Dec 80	0.1659
22	14 Feb 81 (21)	2.3079	08 Feb 81 (1)	0.8748	23 Jun 81	0.1603
23	02 May 81 (24)	2.1999	30 Jul 81 (1)	0.8657	31 May 81	0.1594
24	22 Jul 81 (24)	2.1345	10 Jul 81 (7)	0.8558	12 Nov 81	0.1555
25	09 Jan 81 (09)	2.1078	06 May 81 (1)	0.8147	29 Jul 81	0.1552

TABLE C-3

TWENTY-FIVE HIGHEST SHORT-TERM SO_2 CONCENTRATIONS CALCULATED BY SHORTZ AT MONITOR 4 DURING THE SECOND YEAR OF THE WESTVACO MONITORING PROGRAM

Rank	1-Hour Average Concentrations		3-Hour Average Concentrations		24-Hour Average Concentrations	
	Date (Hour)	Concentration (ppm)	Date (Period)	Concentration (ppm)	Date	Concentration (ppm)
01	04 Dec 80 (20)	5.1199	17 Jun 81 (8)	2.4823	17 Aug 81	0.4258
02	17 Jun 81 (22)	4.0664	04 Dec 80 (7)	2.1496	17 Jun 81	0.4050
03	01 Aug 81 (04)	3.3959	07 May 81 (1)	1.7547	25 Aug 81	0.3889
04	17 Jun 81 (24)	3.3805	25 Aug 81 (1)	1.7084	07 May 81	0.3459
05	14 Feb 81 (21)	2.8275	17 May 81 (8)	1.6818	24 Mar 81	0.3152
06	23 May 81 (04)	2.6215	18 Jul 81 (7)	1.6502	04 Dec 80	0.2752
07	01 May 81 (04)	2.5917	25 Aug 81 (2)	1.2715	17 May 81	0.2738
08	18 Jul 81 (21)	2.5317	17 Aug 81 (2)	1.2188	10 Jul 81	0.2612
09	07 May 81 (03)	2.5029	10 Jul 81 (8)	1.2042	03 May 81	0.2348
10	09 Jan 81 (09)	2.3561	01 Aug 81 (2)	1.1345	18 Jul 81	0.2273
11	17 May 81 (23)	2.2419	20 May 81 (1)	1.0483	15 Jul 81	0.2231
12	25 Aug 81 (04)	2.2166	22 Jul 81 (8)	1.0234	14 Nov 81	0.1917
13	03 May 81 (22)	2.2070	23 May 81 (2)	0.9957	22 Jul 81	0.1836
14	17 Aug 81 (05)	2.1527	03 May 81 (1)	0.9899	01 May 81	0.1825
15	22 Jul 81 (24)	2.1487	29 Jul 81 (8)	0.9567	29 Jul 81	0.1733
16	18 Jul 81 (20)	2.1291	14 Feb 81 (7)	0.9425	26 Jun 81	0.1642
17	03 May 81 (02)	2.0764	24 Mar 81 (2)	0.9285	18 May 81	0.1579
18	25 Aug 81 (02)	2.0632	17 Aug 81 (8)	0.9049	27 Apr 81	0.1531
19	18 May 81 (01)	2.0279	08 Feb 81 (1)	0.8712	23 May 81	0.1426
20	17 May 81 (24)	1.9811	01 May 81 (2)	0.8639	01 Aug 81	0.1418
21	08 Feb 81 (01)	1.9676	26 Jun 81 (8)	0.8385	08 Feb 81	0.1373
22	15 Jul 81 (22)	1.9023	09 Jan 81 (3)	0.7854	25 Mar 81	0.1371
23	29 Jul 81 (24)	1.8892	10 Jul 81 (7)	0.7813	17 Jul 81	0.1345
24	25 Aug 81 (03)	1.8249	03 May 81 (8)	0.7657	20 May 81	0.1325
25	24 Mar 81 (05)	1.8030	10 Apr 81 (1)	0.7470	18 Mar 81	0.1317

TABLE C-4

TWENTY-FIVE HIGHEST SHORT-TERM SO_2 CONCENTRATIONS CALCULATED BY SHORTZ AT MONITOR 5 DURING THE SECOND YEAR OF THE WESTVACO MONITORING PROGRAM

Rank	1-Hour Average Concentrations		3-Hour Average Concentrations		24-Hour Average Concentrations	
	Date (Hour)	Concentration (ppm)	Date (Period)	Concentration (ppm)	Date	Concentration (ppm)
01	06 Aug 81 (04)	1.7645	07 May 81 (2)	1.1889	07 May 81	0.2866
02	29 Dec 80 (09)	1.7342	18 Jul 81 (7)	1.0557	24 Mar 81	0.2096
03	07 May 81 (04)	1.5941	07 May 81 (1)	0.7984	17 Aug 81	0.2024
04	08 Feb 81 (01)	1.5281	17 Jul 81 (7)	0.7245	17 Jul 81	0.1602
05	03 Aug 81 (07)	1.4992	17 May 81 (8)	0.6900	14 Nov 81	0.1460
06	17 Jul 81 (21)	1.4428	06 Aug 81 (2)	0.6874	17 May 81	0.1464
07	27 Apr 81 (07)	1.3583	07 Aug 81 (8)	0.6482	18 Jul 81	0.1374
08	18 Jul 81 (21)	1.2958	14 Nov 81 (7)	0.6186	27 Apr 81	0.1290
09	07 May 81 (03)	1.2863	17 Aug 81 (8)	0.5876	18 May 81	0.1190
10	03 May 81 (22)	1.2841	29 Dec 80 (3)	0.5781	25 Aug 81	0.1160
11	17 Feb 81 (20)	1.2523	03 Aug 81 (3)	0.5299	15 Sep 81	0.0965
12	25 Mar 81 (23)	1.2131	25 Aug 81 (2)	0.5261	07 Aug 81	0.0918
13	07 Aug 81 (24)	1.2114	24 Mar 81 (2)	0.5223	06 Aug 81	0.0867
14	04 May 81 (22)	1.2016	08 Feb 81 (1)	0.5112	03 Aug 81	0.0840
15	17 Aug 81 (22)	1.1844	17 Jun 81 (7)	0.4619	17 Jun 81	0.0817
16	18 Jul 81 (20)	1.1523	27 Apr 81 (3)	0.4528	25 Mar 81	0.0779
17	17 May 81 (22)	1.1334	24 Mar 81 (3)	0.4494	01 May 81	0.0764
18	07 May 81 (06)	1.1144	18 May 81 (2)	0.4350	29 Dec 80	0.0733
19	18 May 81 (04)	1.0966	03 May 81 (8)	0.4280	03 May 81	0.0732
20	23 Jul 81 (01)	1.0622	17 Feb 81 (7)	0.4174	08 Feb 81	0.0728
21	14 Nov 81 (21)	1.0425	17 Aug 81 (2)	0.4064	16 Aug 81	0.0695
22	20 May 81 (02)	1.0061	26 Jun 81 (8)	0.4063	06 May 81	0.0677
23	17 Jun 81 (21)	0.9653	20 May 81 (1)	0.4054	21 Mar 81	0.0653
24	15 Sep 81 (22)	0.9150	25 Mar 81 (8)	0.4044	26 Jun 81	0.0624
25	17 May 81 (23)	0.8910	17 May 81 (7)	0.4022	15 Jul 81	0.0579

TABLE C-5

TWENTY-FIVE HIGHEST SHORT-TERM SO_2 CONCENTRATIONS CALCULATED BY SHORTZ AT MONITOR 6 DURING THE SECOND YEAR OF THE WESTVACO MONITORING PROGRAM

Rank	1-Hour Average Concentrations		3-Hour Average Concentrations		24-Hour Average Concentrations	
	Date (Hour)	Concentration (ppm)	Date (Period)	Concentration (ppm)	Date	Concentration (ppm)
01	20 May 81 (23)	9.2365	20 May 81 (8)	3.1442	22 May 81	0.8225
02	13 Nov 81 (06)	8.3246	29 Dec 80 (8)	2.9067	29 Dec 80	0.7722
03	23 May 81 (06)	4.9185	23 May 81 (8)	2.8897	21 May 81	0.7210
04	09 Nov 81 (09)	4.8016	13 Nov 81 (2)	2.7749	23 May 81	0.6912
05	11 Jul 81 (23)	4.7761	31 Jul 81 (1)	2.6077	06 Jul 81	0.6296
06	14 Aug 81 (21)	4.5817	07 Apr 81 (1)	2.4424	04 May 81	0.5938
07	29 Dec 80 (24)	4.4951	14 Aug 81 (7)	2.3394	20 May 81	0.5794
08	07 Apr 81 (03)	4.4921	06 Jul 81 (8)	2.3120	03 Nov 81	0.5755
09	01 Nov 81 (09)	4.4405	21 May 81 (1)	2.1010	08 Feb 81	0.5553
10	21 Aug 81 (07)	4.2338	16 Nov 81 (8)	2.0966	16 Nov 81	0.5393
11	31 Jul 81 (01)	4.0898	04 May 81 (2)	2.0463	03 Aug 81	0.5378
12	23 May 81 (24)	4.0532	03 Nov 81 (2)	2.0037	09 Sep 81	0.5081
13	22 May 81 (23)	3.9886	22 May 81 (1)	1.9546	27 Jul 81	0.5051
14	07 Jun 81 (21)	3.9400	21 May 81 (8)	1.9279	30 Jul 81	0.4963
15	06 Jul 81 (21)	3.8995	17 Jul 81 (1)	1.9278	09 Nov 81	0.4913
16	18 Jul 81 (23)	3.8884	03 Aug 81 (8)	1.9037	17 Jul 81	0.4845
17	31 Jul 81 (02)	3.7332	26 Sep 81 (2)	1.8629	29 Sep 81	0.4688
18	29 Jun 81 (20)	3.7054	11 Jul 81 (8)	1.8244	07 Dec 80	0.4673
19	27 Jul 81 (21)	3.5055	15 Jul 81 (8)	1.7932	15 Nov 81	0.4526
20	27 Jul 81 (22)	3.4120	22 May 81 (2)	1.7584	17 Nov 81	0.4391
21	08 Feb 81 (04)	3.4070	09 Sep 81 (8)	1.7330	28 Oct 81	0.4311
22	23 May 81 (23)	3.3534	23 Jul 81 (2)	1.7005	06 Dec 80	0.4192
23	01 Aug 81 (06)	3.3010	23 May 81 (2)	1.6398	18 Sep 81	0.4081
24	21 May 81 (02)	3.1703	17 Nov 81 (1)	1.6301	31 Jul 81	0.4071
25	26 Sep 81 (05)	3.1527	28 Oct 81 (7)	1.6263	15 Jul 81	0.4051

TABLE C-6

TWENTY-FIVE HIGHEST SHORT-TERM SO_2 CONCENTRATIONS CALCULATED BY SHORTZ AT MONITOR 7 DURING THE SECOND YEAR OF THE WESTVACO MONITORING PROGRAM

Rank	1-Hour Average Concentrations		3-Hour Average Concentrations		24-Hour Average Concentrations	
	Date (Hour)	Concentration (ppm)	Date (Period)	Concentration (ppm)	Date	Concentration (ppm)
01	29 Dec 80 (09)	2.1438	07 May 81 (2)	1.2483	07 May 81	0.2330
02	04 May 81 (22)	1.8379	07 Aug 81 (8)	0.9606	24 Mar 81	0.1610
03	06 Aug 81 (04)	1.5619	29 Dec 80 (3)	0.7146	17 Jul 81	0.1583
04	07 Aug 81 (23)	1.5539	21 Mar 81 (8)	0.7070	17 Aug 81	0.1458
05	01 May 81 (01)	1.4955	06 Aug 81 (2)	0.6663	14 Nov 81	0.1455
06	17 Feb 81 (20)	1.4708	17 Jul 81 (7)	0.6644	07 Aug 81	0.1271
07	17 May 81 (22)	1.4034	04 May 81 (8)	0.6126	18 May 81	0.1140
08	18 Jul 81 (19)	1.3720	18 Jul 81 (7)	0.5898	18 Aug 81	0.1093
09	07 May 81 (05)	1.3359	14 Nov 81 (7)	0.5600	21 Mar 81	0.1004
10	07 Aug 81 (24)	1.3279	17 May 81 (8)	0.5086	17 May 81	0.0993
11	28 Dec 80 (18)	1.3180	01 May 81 (1)	0.4985	01 May 81	0.0968
12	08 Feb 81 (01)	1.2708	17 Feb 81 (7)	0.4903	29 Dec 80	0.0894
13	22 Jul 81 (23)	1.2640	18 May 81 (2)	0.4792	06 Aug 81	0.0833
14	07 May 81 (06)	1.2345	18 Aug 81 (2)	0.4400	27 Apr 81	0.0811
15	17 Jul 81 (20)	1.2234	28 Dec 80 (6)	0.4398	04 May 81	0.0784
16	07 May 81 (04)	1.1743	17 Jun 81 (7)	0.4234	28 Dec 80	0.0774
17	14 Nov 81 (20)	1.1126	08 Feb 81 (1)	0.4236	18 Jul 81	0.0745
18	16 Dec 80 (06)	1.0949	22 Jul 81 (8)	0.4232	17 Feb 81	0.0613
19	17 Jun 81 (21)	1.0201	05 Aug 81 (8)	0.4085	06 May 81	0.0589
20	20 May 81 (02)	0.9925	28 May 81 (8)	0.3958	16 Dec 80	0.0559
21	07 May 81 (07)	0.9542	17 Aug 81 (1)	0.3912	23 Mar 81	0.0557
22	17 Aug 81 (06)	0.9494	24 Mar 81 (2)	0.3824	22 Jul 81	0.0556
23	17 Jul 81 (06)	0.9407	16 Dec 80 (2)	0.3650	08 Feb 81	0.0546
24	17 Aug 81 (02)	0.7899	07 May 81 (3)	0.3566	17 Jun 81	0.0532
25	21 Mar 81 (22)	0.7866	24 Mar 81 (3)	0.3527	15 Sep 81	0.0518

TABLE C-7

TWENTY-FIVE HIGHEST SHORT-TERM SO_2 CONCENTRATIONS CALCULATED BY SHORTZ AT MONITOR 8 DURING THE SECOND YEAR OF THE WESTVACO MONITORING PROGRAM

Rank	1-Hour Average Concentrations		3-Hour Average Concentrations		24-Hour Average Concentrations	
	Date (Hour)	Concentration (ppm)	Date (Period)	Concentration (ppm)	Date	Concentration (ppm)
01	07 Aug 81 (23)	1.2892	07 Aug 81 (8)	0.6529	18 May 81	0.0922
02	29 Dec 80 (09)	1.0728	21 Mar 81 (8)	0.5838	07 Aug 81	0.0821
03	28 Dec 80 (18)	1.0373	18 May 81 (7)	0.3804	21 Mar 81	0.0731
04	16 Dec 80 (06)	0.9581	29 Dec 80 (3)	0.3576	28 Dec 80	0.0731
05	30 Sep 81 (03)	0.8018	28 Dec 80 (6)	0.3546	18 Aug 81	0.0625
06	07 Aug 81 (24)	0.6694	16 Dec 80 (2)	0.3194	14 Nov 81	0.0620
07	17 Feb 81 (20)	0.6579	18 May 81 (2)	0.2897	16 Dec 80	0.0543
08	21 Mar 81 (23)	0.6329	18 Aug 81 (2)	0.2658	29 Dec 80	0.0471
09	21 Mar 81 (24)	0.6311	03 May 81 (7)	0.2298	01 May 81	0.0431
10	03 May 81 (21)	0.6221	28 May 81 (8)	0.2286	17 Aug 81	0.0402
11	18 May 81 (21)	0.6065	17 Feb 81 (7)	0.2193	17 Jul 81	0.0378
12	04 May 81 (22)	0.5800	14 Nov 81 (7)	0.2002	07 May 81	0.0365
13	01 May 81 (01)	0.5326	18 Aug 81 (1)	0.1948	30 Sep 81	0.0365
14	18 Jul 81 (19)	0.5323	04 May 81 (8)	0.1933	24 Mar 81	0.0347
15	21 Mar 81 (22)	0.4875	06 Aug 81 (2)	0.1919	03 May 81	0.0311
16	18 May 81 (05)	0.4868	07 May 81 (2)	0.1826	28 May 81	0,0289
17	22 Jul 81 (23)	0.4586	18 Jul 81 (7)	0.1778	17 Feb 81	0.0274
18	17 Aug 81 (06)	0.3796	01 May 81 (1)	0.1775	27 Apr 81	0.0260
19	17 Jul 81 (20)	0.3743	05 Aug 81 (8)	0.1548	04 May 81	0.0242
20	05 Aug 81 (24)	0.3664	22 Jul 81 (8)	0.1529	06 Aug 81	0.0240
21	01 May 81 (09)	0.3650	13 Nov 81 (8)	0.1373	15 Sep 81	0.0230
22	14 Nov 81 (20)	0.3549	17 Jul 81 (7)	0.1315	18 Jul 81	0.0222
23	18 May 81 (06)	0.3541	27 Apr 81 (2)	0.1295	17 May 81	0.0205
24	17 May 81 (22)	0.3482	17 Aug 81 (2)	0.1265	09 Nov 81	0.0204
25	16 Dec 80 (07)	0.3450	17 Jul 81 (3)	0.1227	05 Aug 81	0.0194

TABLE C-8

TWENTY-FIVE HIGHEST SHORT-TERM SO_2 CONCENTRATIONS CALCULATED BY SHORTZ AT MONITOR 9 DURING THE SECOND YEAR OF THE WESTVACO MONITORING PROGRAM

Rank	1-Hour Average Concentrations		3-Hour Average Concentrations		24-Hour Average Concentrations	
	Date (Hour)	Concentration (ppm)	Date (Period)	Concentration (ppm)	Date	Concentration (ppm)
01	29 Dec 80 (09)	1.3754	07 Aug 81 (8)	0.7543	07 May 81	0.1029
02	07 Aug 81 (24)	1.2377	07 May 81 (2)	0.5581	07 Aug 81	0.0974
03	07 Aug 81 (23)	1.0251	29 Dec 80 (3)	0.4585	18 May 81	0.0868
04	17 Feb 81 (20)	1.0248	18 May 81 (7)	0.3718	24 Mar 81	0.0765
05	04 May 81 (22)	0.9263	06 Aug 81 (2)	0.3633	17 Jul 81	0.0687
06	06 Aug 81 (04)	0.8528	21 Mar 81 (8)	0.3602	14 Nov 81	0.0682
07	01 May 81 (01)	0.7691	17 Feb 81 (7)	0.3416	17 Aug 81	0.0672
08	28 Dec 80 (18)	0.7157	04 May 81 (8)	0.3088	29 Dec 80	0.0573
09	16 Dec 80 (06)	0.7002	17 Jul 81 (7)	0.2908	01 May 81	0.0529
10	17 May 81 (22)	0.6890	14 Nov 81 (7)	0.2764	27 Apr 81	0.0519
11	18 Jul 81 (19)	0.6598	15 Sep 81 (6)	0.2722	15 Sep 81	0.0506
12	08 Feb 81 (01)	0.6313	18 Jul 81 (7)	0.2662	21 Mar 81	0.0499
13	22 Jul 81 (23)	0.6087	01 May 81 (1)	0.2564	18 Aug 81	0.0496
14	07 May 81 (05)	0.6065	17 May 81 (8)	0.2433	17 May 81	0.0461
15	03 Aug 81 (07)	0.5712	28 Dec 80 (6)	0.2388	06 Aug 81	0.0454
16	17 Jul 81 (20)	0.5641	18 May 81 (2)	0.2362	28 Dec 80	0.0431
17	14 Nov 81 (20)	0.5514	16 Dec 80 (2)	0.2334	17 Feb 81	0.0427
18	07 May 81 (06)	0.5495	08 Feb 81 (1)	0.2104	04 May 81	0.0392
19	07 May 81 (04)	0.5181	28 May 81 (8)	0.2086	16 Dec 80	0.0350
20	17 Jun 81 (21)	0.4568	22 Jul 81 (8)	0.2033	18 Jul 81	0.0335
21	27 Apr 81 (06)	0.4421	18 Aug 81 (2)	0.2015	03 Aug 81	0.0298
22	20 May 81 (02)	0.4382	27 Apr 81 (2)	0.1988	06 May 81	0.0282
23	07 May 81 (07)	0.4247	03 Aug 81 (3)	0.1946	08 Feb 81	0.0269
24	18 Aug 81 (06)	0.4245	05 Aug 81 (8)	0.1872	22 Jul 81	0.0264
25	15 Sep 81 (18)	0.4234	17 Jun 81 (7)	0.1861	28 May 81	0.0261

TABLE C-9

TWENTY-FIVE HIGHEST SHORT-TERM SO_2 CONCENTRATIONS CALCULATED BY SHORTZ AT MONITOR 10 DURING THE SECOND YEAR OF THE WESTVACO MONITORING PROGRAM

Rank	1-Hour Average Concentrations		3-Hour Average Concentrations		24-Hour Average Concentrations	
	Date (Hour)	Concentration (ppm)	Date (Period)	Concentration (ppm)	Date	Concentration (ppm)
01	13 Jan 81 (08)	0.1992	07 Apr 81 (8)	0.1591	18 Feb 81	0.0458
02	08 Apr 81 (01)	0.1718	08 Apr 81 (2)	0.1338	08 Apr 81	0.0414
03	23 May 81 (08)	0.1663	23 May 81 (3)	0.1268	13 Jan 81	0.0390
04	07 Apr 81 (23)	0.1648	08 Apr 81 (1)	0.1257	16 Apr 81	0.0325
05	23 Feb 81 (20)	0.1640	13 Jan 81 (2)	0.1226	02 Dec 80	0.0301
06	07 Apr 81 (22)	0.1627	18 Feb 81 (2)	0.1210	05 Nov 81	0.0267
07	06 Feb 81 (05)	0.1564	21 Sep 81 (8)	0.1171	07 Apr 81	0.0263
08	08 Apr 81 (05)	0.1534	18 Feb 81 (1)	0.1051	17 Feb 81	0.0257
09	07 Apr 81 (24)	0.1498	23 Feb 81 (7)	0.1045	26 Mar 81	0.0250
10	08 Apr 81 (04)	0.1460	13 Jan 81 (3)	0.0965	15 Aug 81	0.0250
11	06 Jul 81 (03)	0.1437	06 Feb 81 (2)	0.0883	27 Aug 81	0.0243
12	18 Feb 81 (04)	0.1435	09 Feb 81 (8)	0.0854	20 Oct 81	0.0242
13	09 Nov 81 (08)	0.1421	26 May 81 (2)	0.0847	04 Mar 81	0.0234
14	08 Apr 81 (02)	0.1394	16 Apr 81 (8)	0.0822	08 Jun 81	0.0226
15	28 Feb 81 (05)	0.1378	04 Mar 81 (2)	0.0821	06 Feb 81	0.0220
16	23 Nov 81 (19)	0.1346	16 Apr 81 (1)	0.0820	03 Apr 81	0.0219
17	21 Sep 81 (23)	0.1335	15 Aug 81 (2)	0.0793	06 Jan 81	0.0214
18	18 Feb 81 (06)	0.1327	06 Jul 81 (1)	0.0793	23 Feb 81	0.0203
19	13 Jan 81 (04)	0.1289	06 Oct 81 (2)	0.0787	25 May 81	0.0199
20	07 Feb 81 (07)	0.1259	17 Feb 81 (8)	0.0777	26 May 81	0.0198
21	18 Oct 81 (05)	0.1229	13 Jan 81 (1)	0.0777	14 Sep 81	0.0195
22	17 Apr 81 (01)	0.1221	09 Nov 81 (3)	0.0776	04 Oct 81	0.0194
23	23 Mar 81 (07)	0.1218	25 May 81 (1)	0.0768	09 Nov 81	0.0192
24	13 Jan 81 (06)	0.1210	06 Feb 81 (1)	0.0750	19 Jul 81	0.0185
25	16 Apr 81 (23)	0.1194	26 Sep 81 (8)	0.0730	21 Sep 81	0.0182

TABLE C-10

ANNUAL AVERAGE SO_2 CONCENTRATIONS CALCULATED BY SHORTZ FOR THE SECOND YEAR OF THE WESTVACO MONITORING PROGRAM

Site	No. of Hours of Valid Data	Annual Average Concentration (ppm)
1	8,742	0.0905
3	8,742	0.0422
4	8,742	0.0279
5	8,742	0.0116
6	8,742	0.1573
7	8,742	0.0092
8	8,742	0.0037
9	8,742	0.0048
10	8,742	0.0045

TABLE C-11

TWENTY-FIVE HIGHEST 1-HOUR SO_2 CONCENTRATIONS CALCULATED BY SHORTZ AT ALL MONITORS DURING THE SECOND YEAR OF THE WESTVACO MONITORING PROGRAM

Rank	Monitor	Date (Hour)	Concentration (ppm)
1	6	20 May 81 (23)	9.2365
2	6	13 Nov 81 (06)	8.3246
3	1	29 Dec 80 (10)	6.8795
4	3	3 May 81 (23)	6.5644
5	3	23 May 81 (04)	6.5305
6	1	26 Nov 81 (23)	5.8871
7	3	23 May 81 (03)	5.8840
8	3	23 May 81 (05)	5.7796
9	1	18 May 81 (02)	5.7255
10	1	4 Nov 81 (21)	5.4999
11	4	4 Dec 80 (20)	5.1199
12	6	23 May 81 (06)	4.9185
13	6	9 Nov 81 (09)	4.8016
14	6	11 Jul 81 (23)	4.7761
15	1	17 Feb 81 (21)	4.7498
16	1	12 Feb 81 (22)	4.5901
17	6	14 Aug 81 (21)	4.5817
18	1	4 Dec 80 (21)	4.5057
19	6	29 Dec 80 (24)	4.4951
20	6	7 Apr 81 (03)	4.4921
21	6	1 Nov 81 (09)	4.4405
22	1	2 May 81 (23)	4.2689
23	1	3 May 81 (24)	4.2618
24	6	21 Aug 81 (07)	4.2338
25	6	31 Jul 81 (01)	4.0898

TABLE C-12

TWENTY-FIVE HIGHEST 3-HOUR SO_2 CONCENTRATIONS CALCULATED BY SHORTZ AT ALL MONITORS DURING THE SECOND YEAR OF THE WESTVACO MONITORING PROGRAM

Rank	Monitor	Date (Hour)	Concentration (ppm)
1	3	23 May 81 (2)	4.1034
2	1	18 May 81 (1)	3.1736
3	1	4 Nov 81 (7)	3.1540
4	6	20 May 81 (8)	3.1442
5	6	29 Dec 80 (8)	2.9067
6	6	23 May 81 (8)	2.8897
7	6	13 Nov 81 (2)	2.7749
8	6	31 Jul 81 (1)	2.6077
9	1	29 Dec 80 (4)	2.5622
10	3	23 May 81 (1)	2.5276
11	4	17 Jun 81 (8)	2.4823
12	1	4 Dec 80 (7)	2.4438
13	6	7 Apr 81 (1)	2.4424
14	1	23 May 81 (1)	2.3912
15	1	8 Feb 81 (1)	2.3584
16	3	3 May 81 (8)	2.3627
17	1	2 May 81 (8)	2.3532
18	6	14 Aug 81 (7)	2.3394
19	6	6 Jul 81 (8)	2.3120
20	1	29 Dec 80 (7)	2.2477
21	4	4 Dec 80 (7)	2.1496
22	3	3 May 81 (1)	2.1184
23	6	21 May 81 (1)	2.1010
24	6	16 Nov 81 (8)	2.0966
25	6	4 May 81 (2)	2.0463

TABLE C-13

TWENTY-FIVE HIGHEST 24-HOUR SO_2 CONCENTRATIONS CALCULATED BY SHORTZ AT ALL MONITORS DURING THE SECOND YEAR OF THE WESTVACO MONITORING PROGRAM

Rank	Monitor	Date (Hour)	Concentration (ppm)
1	3	23 May 81	0.8503
2	6	22 May 81	0.8225
3	6	29 Dec 80	0.7722
4	6	21 May 81	0.7210
5	1	29 Dec 80	0.7163
6	6	23 May 81	0.6912
7	1	8 Feb 81	0.6694
8	3	3 May 81	0.6660
9	6	6 Jul 81	0.6296
10	1	6 May 81	0.6067
11	6	4 May 81	0.5938
12	1	23 May 81	0.5918
13	6	20 May 81	0.5794
14	6	3 Nov 81	0.5755
15	6	8 Feb 81	0.5553
16	6	16 Nov 81	0.5393
17	6	3 Aug 81	0.5378
18	1	18 May 81	0.5175
19	1	7 Jun 81	0.5140
20	6	9 Sep 81	0.5081
21	6	27 Jul 81	0.5051
22	3	17 Aug 81	0.4989
23	6	30 Jul 81	0.4963
24	6	9 Nov 81	0.4913
25	1	3 Aug 81	0.4894

APPENDIX D

CUMMULATIVE FREQUENCY DISTRIBUTIONS OF THE 25 HIGHEST OBSERVED (MINUS BACKGROUND) AND CALCULATED (SHORTZ) SHORT-TERM SO_2 CONCENTRATIONS

This appendix compares the cumulative frequency distributions of the 25 highest short-term (1-hour, 3-hour and 24-hour average) observed (minus background) SO_2 concentrations from Appendix B with the corresponding cumulative frequency distributions of the 25 highest calculated (SHORTZ) short-term concentrations from Appendix C. Table D-1 gives the figure number for each combination of monitor and concentration averaging time.

TABLE D-1

IDENTIFICATION OF FIGURE NUMBERS BY MONITOR AND CONCENTRATION AVERAGING TIME

Figure No.	Monitor	Averaging Time
D-1	1	1 Hour
D-2	1	3 Hours
D-3	1	24 Hours
D-4	3	1 Hour
D-5	3	3 Hours
D-6	3	24 Hours
D-7	4	1 Hour
D-8	4	3 Hours
D-9	4	24 Hours
D-10	5	1 Hour
D-11	5	3 Hours
D-12	5	24 Hours
D-13	6	1 Hour
D-14	6	3 Hours
D-15	6	24 Hours
D-16	7	1 Hour
D-17	7	3 Hours
D-18	7	24 Hours
D-19	8	1 Hour
D-20	8	3 Hours
D-21	8	24 Hours
D-22	9	1 Hour
D-23	9	3 Hours
D-24	9	24 Hours
D-25	10	1 Hour
D-26	10	3 Hours
D-27	10	24 Hours
D-28	All	1 Hour
D-29	All	3 Hours
D-30	All	24 Hours

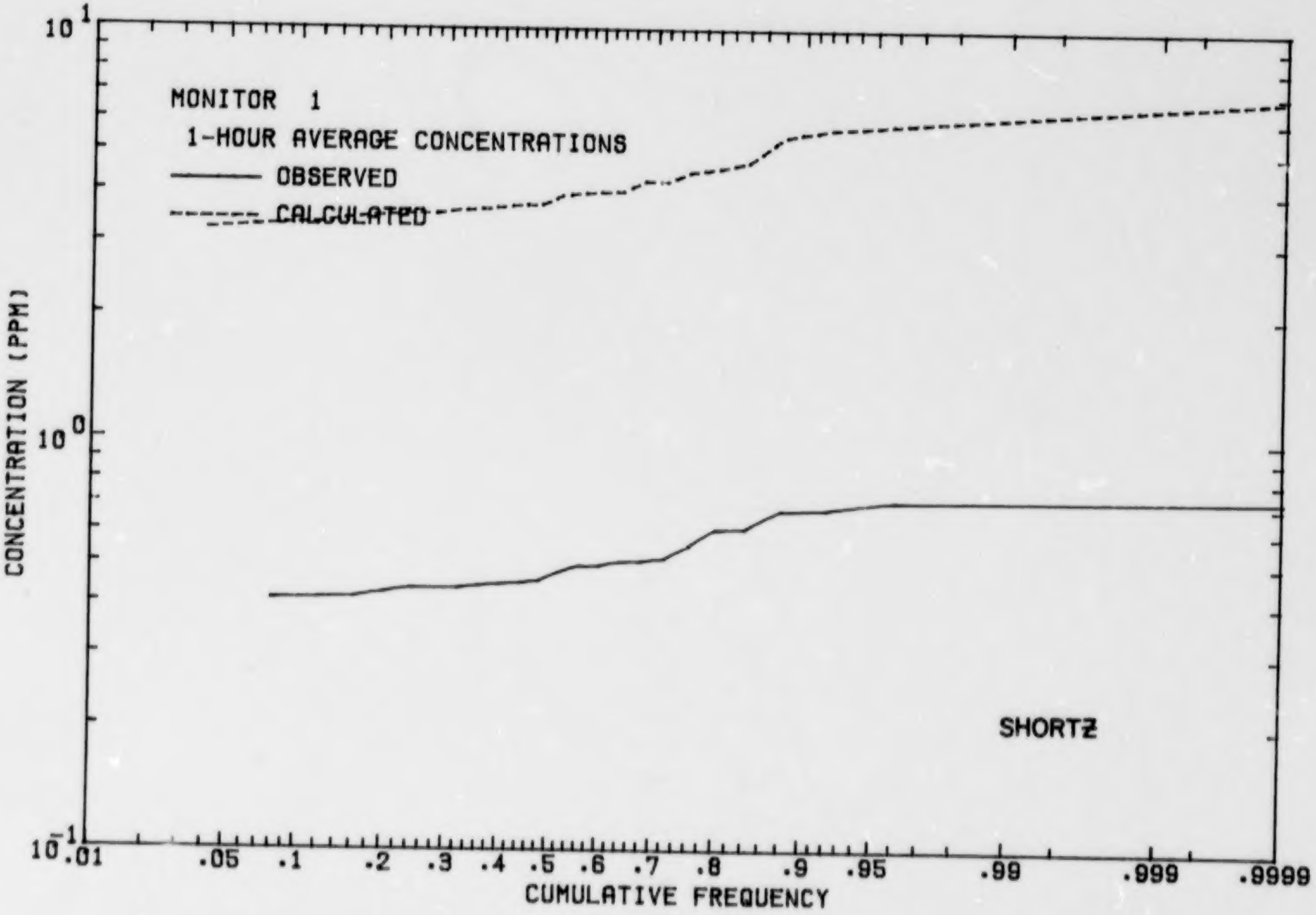

Figure D-1. Comparison of the cumulative frequency distribution of the 25 highest observed (minus background) 1-hour average SO_2 concentrations at Monitor 1 during the second year of the Westvaco monitoring program with the cumulative frequency distribution of the 25 highest 1-hour average concentrations calculated by SHORTZ.

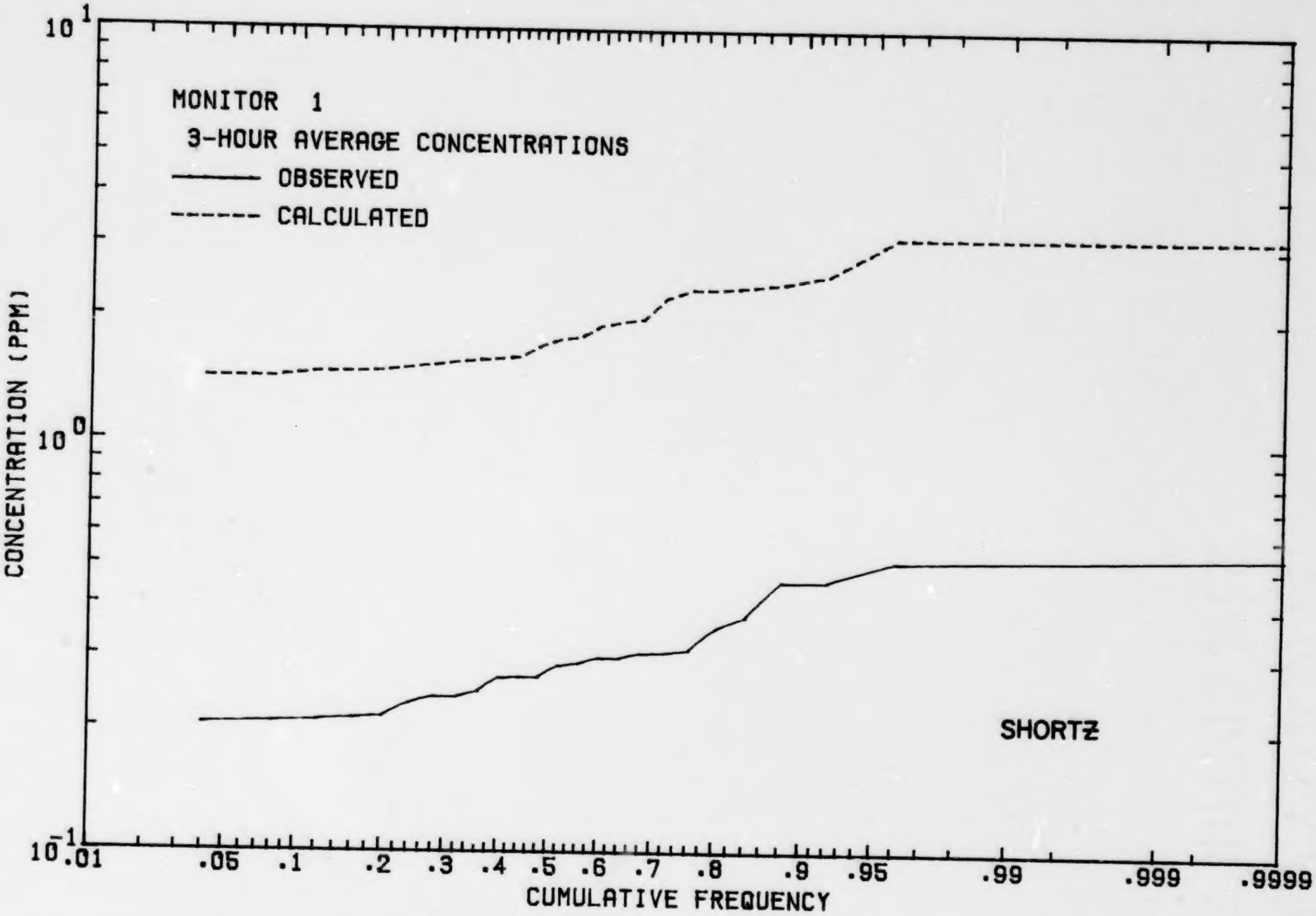

Figure D-2. Comparison of the cumulative frequency distribution of the 25 highest observed (minus background) 3-hour average SO_2 concentrations at Monitor 1 during the second year of the Westvaco monitoring program with the cumulative frequency distribution of the 25 highest 3-hour average concentrations calculated by SHORTZ.

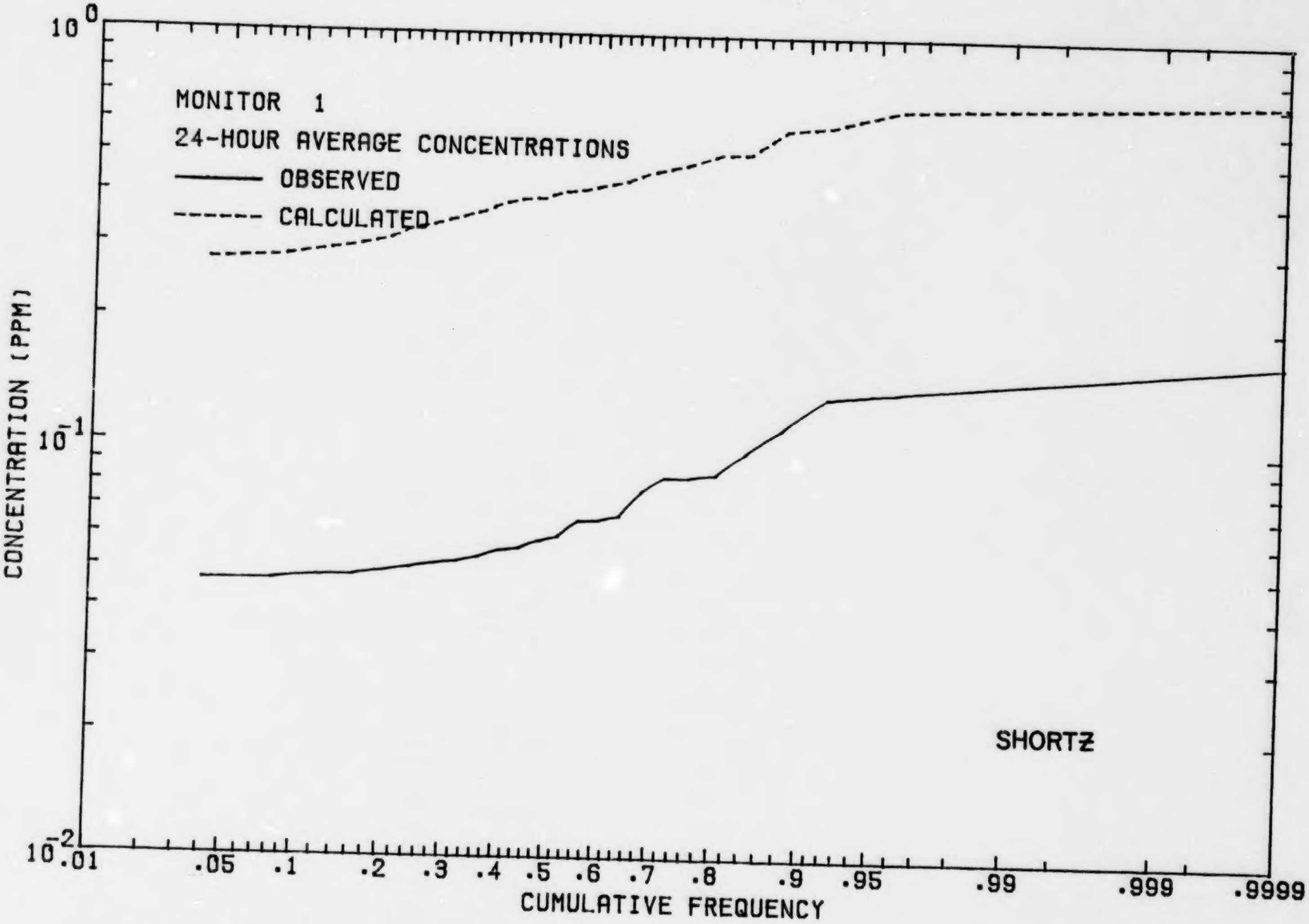

Figure D-3. Comparison of the cumulative frequency distribution of the 25 highest observed (minus background) 24-hour average SO_2 concentrations at Monitor 1 during the second year of the Westvaco monitoring program with the cumulative frequency distribution of the 25 highest 24-hour average concentrations calculated by SHORTZ.

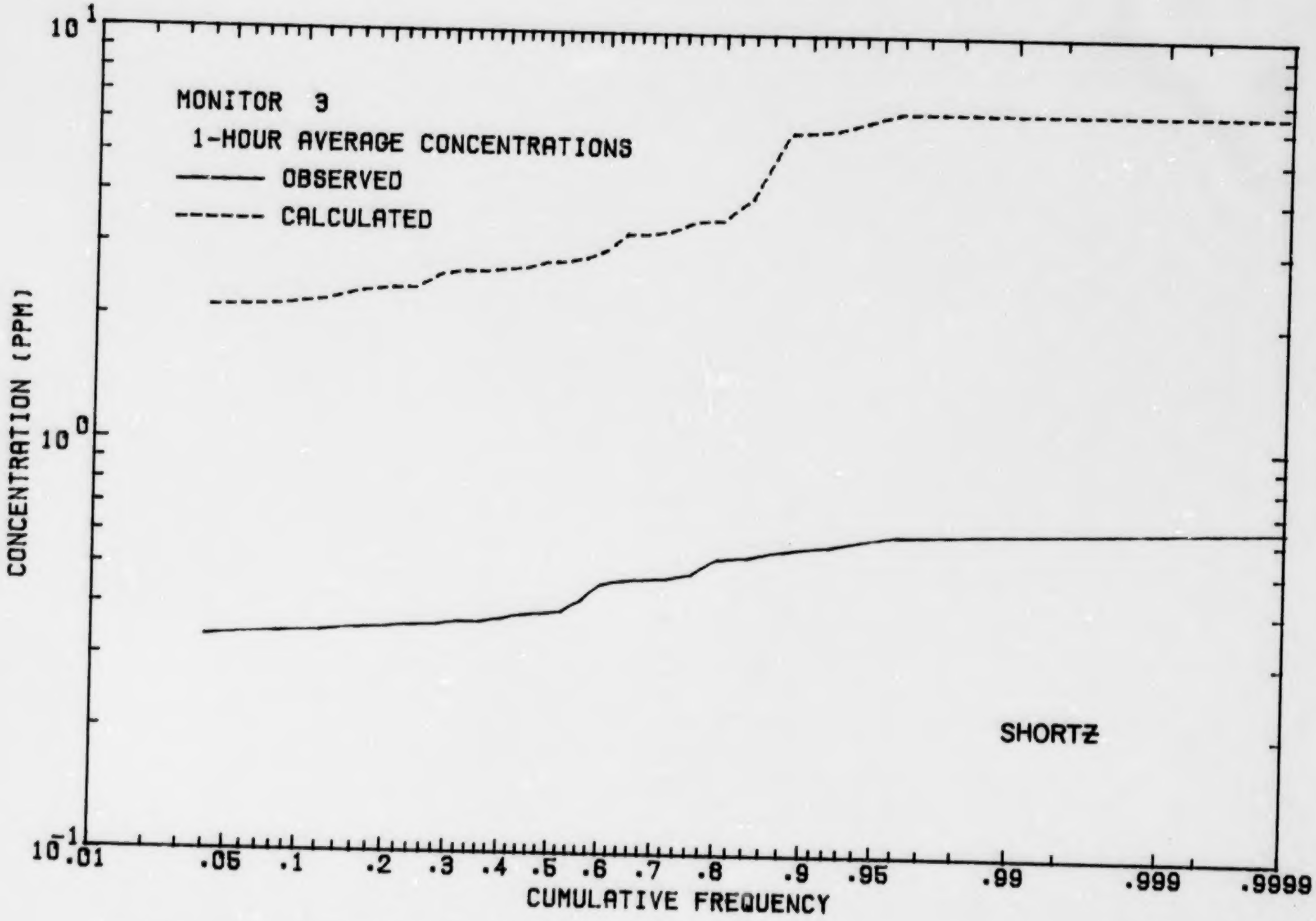

Figure D-4. Comparison of the cumulative frequency distribution of the 25 highest observed (minus background) 1-hour average SO_2 concentrations at Monitor 3 during the second year of the Westvaco monitoring program with the cumulative frequency distribution of the 25 highest 1-hour average concentrations calculated by SHORTZ.

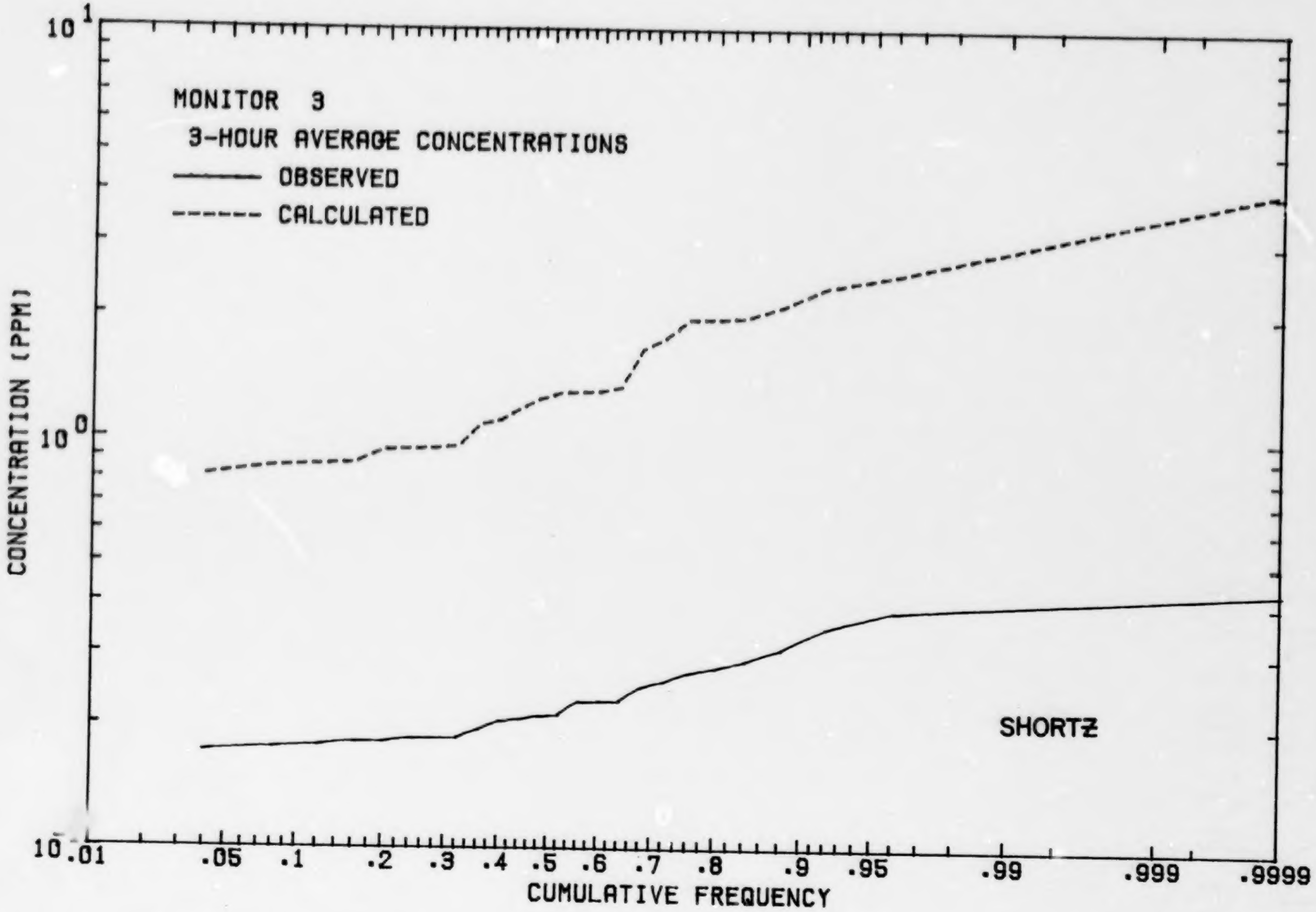

Figure D-5. Comparison of the cumulative frequency distribution of the 25 highest observed (minus background) 3-hour average SO_2 concentrations at Monitor 3 during the second year of the Westvaco monitoring program with the cumulative frequency distribution of the 25 highest 3-hour average concentrations calculated by SHORTZ.

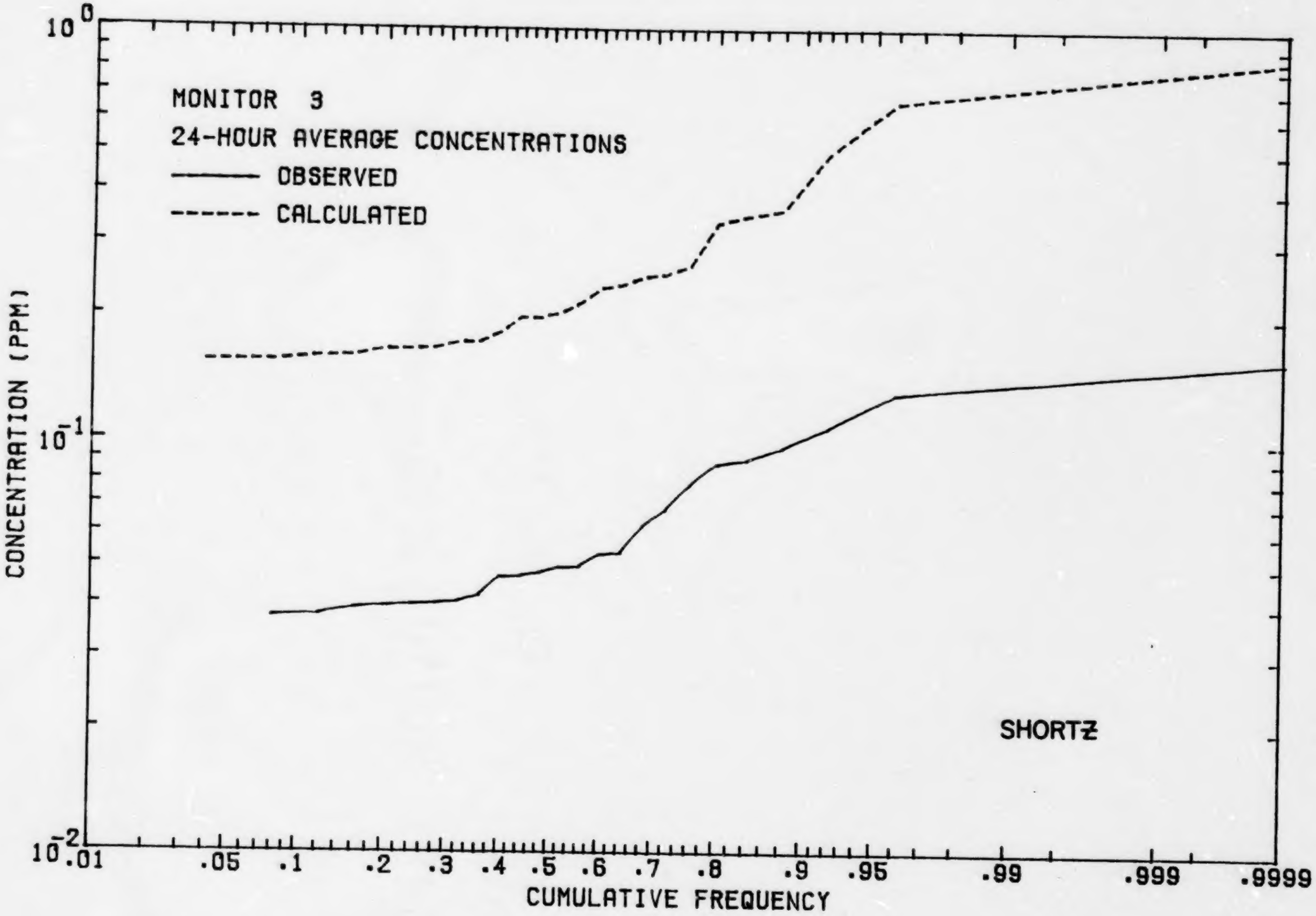

Figure D-6. Comparison of the cumulative frequency distribution of the 25 highest observed (minus background) 24-hour average SO_2 concentrations at Monitor 3 during the second year of the Westvaco monitoring program with the cumulative frequency distribution of the 25 highest 24-hour average concentrations calculated by SHORTZ.

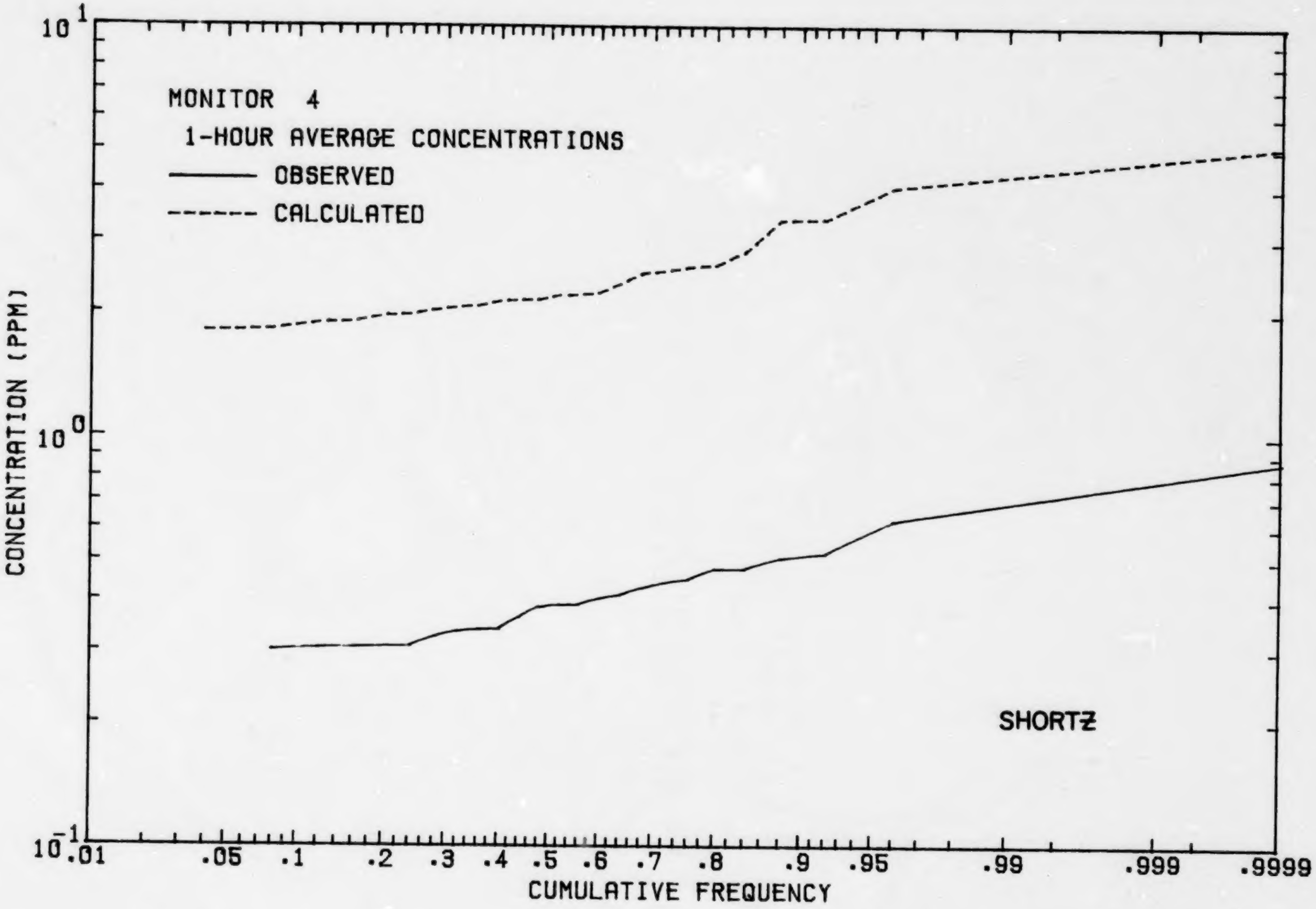

Figure D-7. Comparison of the cumulative frequency distribution of the 25 highest observed (minus background) 1-hour average SO_2 concentrations at Monitor 4 during the second year of the Westvaco monitoring program with the cumulative frequency distribution of the 25 highest 1-hour average concentrations calculated by SHORTZ.

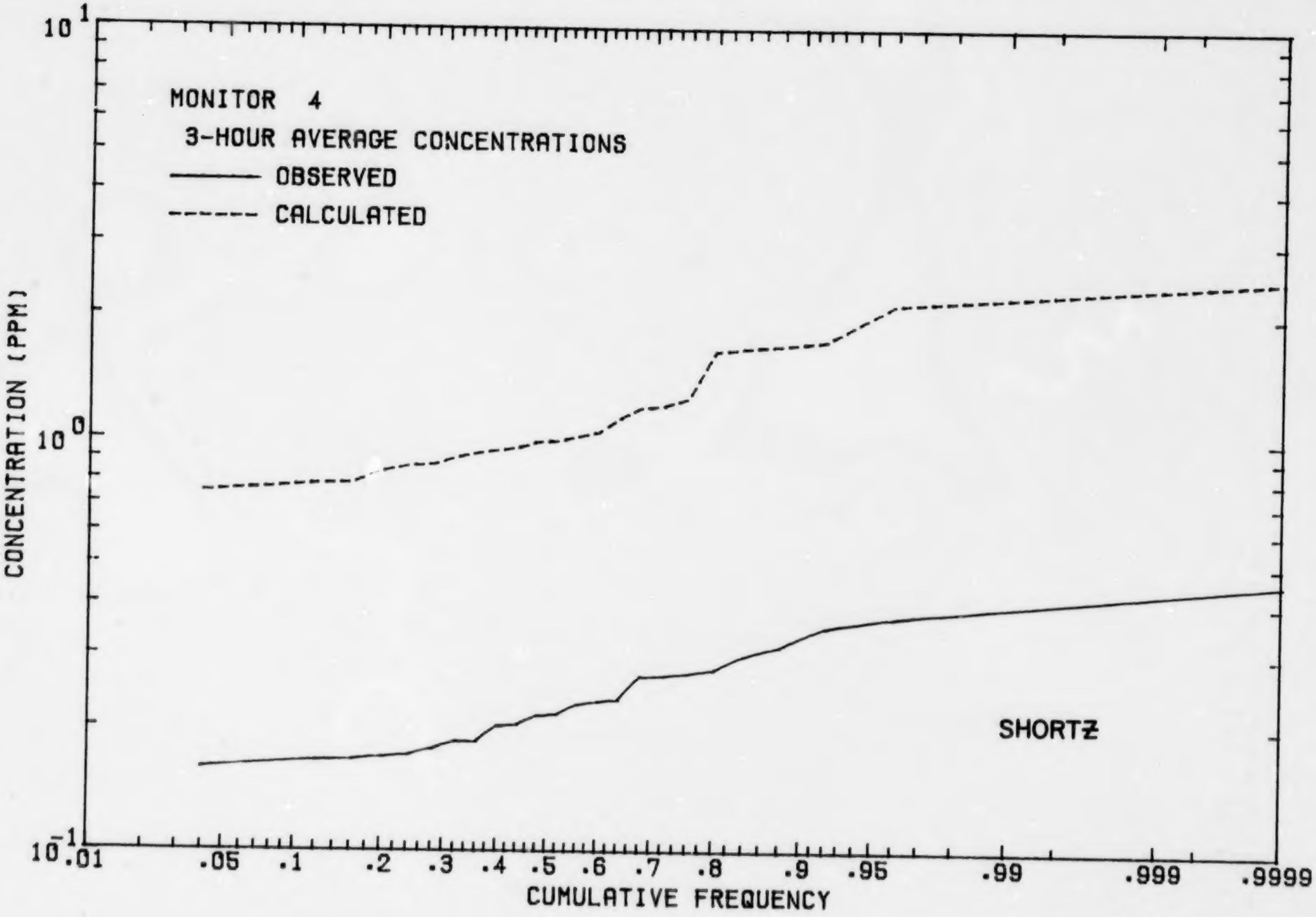

Figure D-8. Comparison of the cumulative frequency distribution of the 25 highest observed (minus background) 3-hour average SO_2 concentrations at Monitor 4 during the second year of the Westvaco monitoring program with the cumulative frequency distribution of the 25 highest 3-hour average concentrations calculated by SHORTZ.

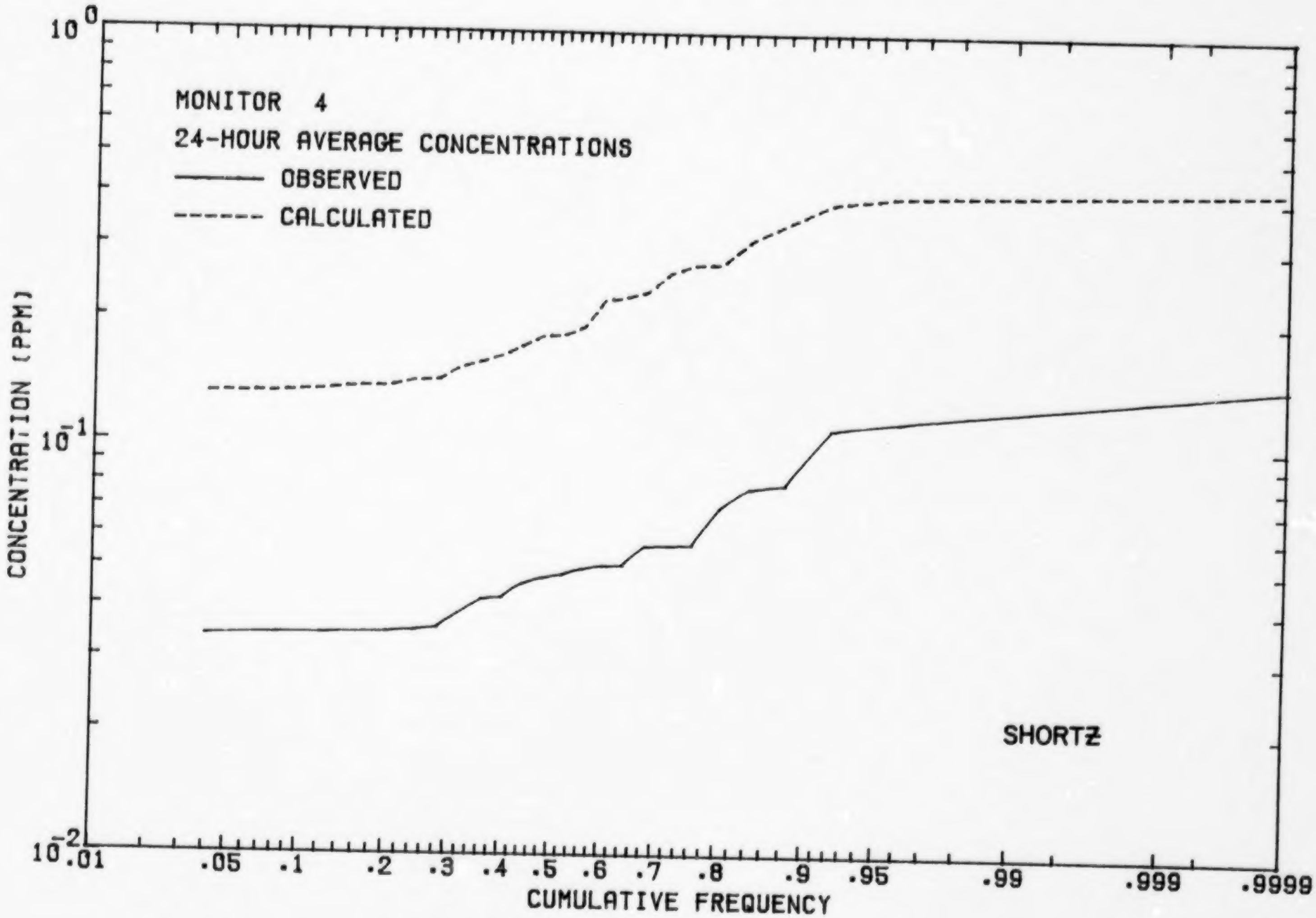

Figure D-9. Comparison of the cumulative frequency distribution of the 25 highest observed (minus background) 24-hour average SO_2 concentrations at Monitor 4 during the second year of the Westvaco monitoring program with the cumulative frequency distribution of the 25 highest 24-hour average concentrations calculated by SHORTZ.

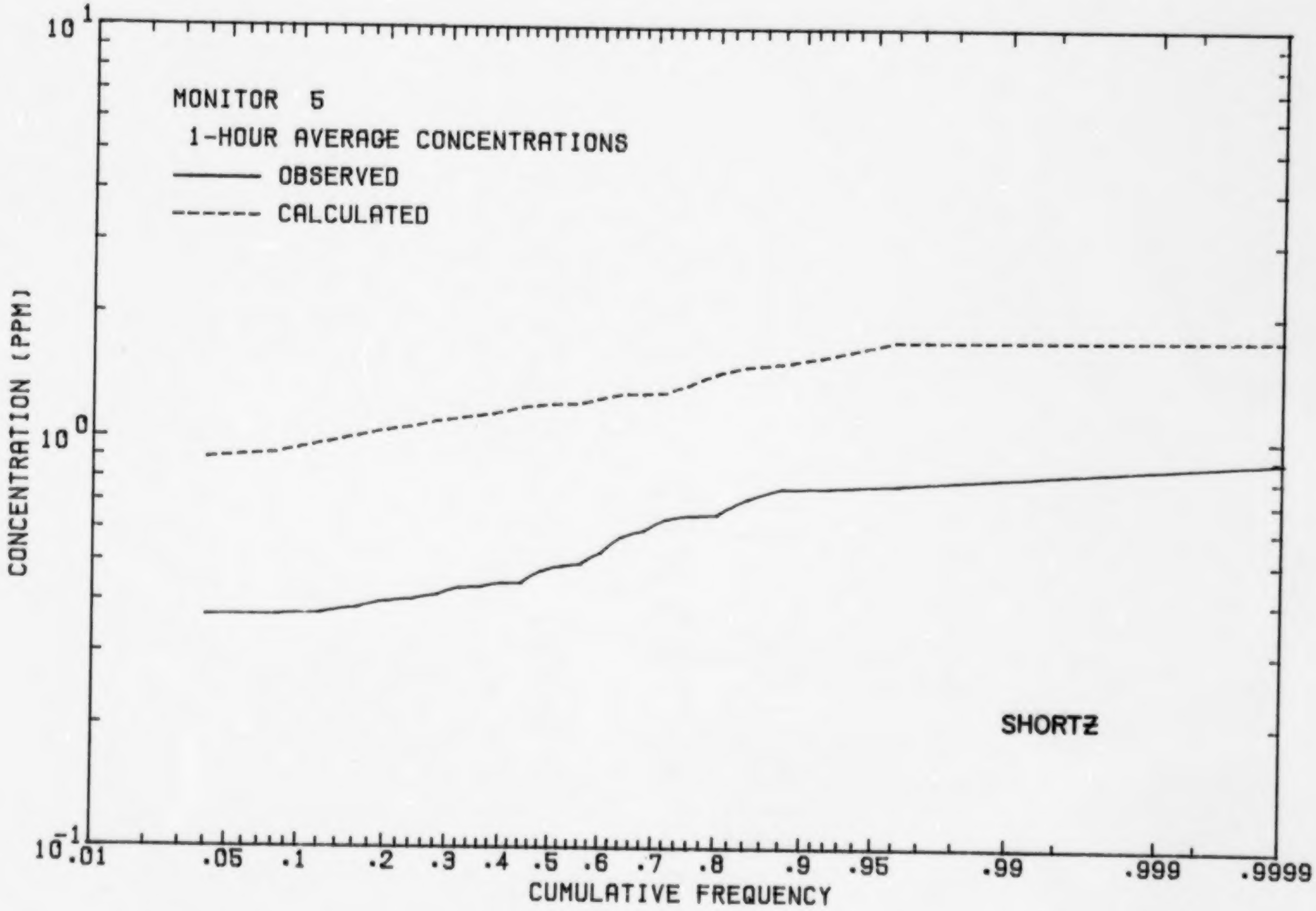

Figure D-10. Comparison of the cumulative frequency distribution of the 25 highest observed (minus background) 1-hour average SO_2 concentrations at Monitor 5 during the second year of the Westvaco monitoring program with the cumulative frequency distribution of the 25 highest 1-hour average concentrations calculated by SHORTZ.

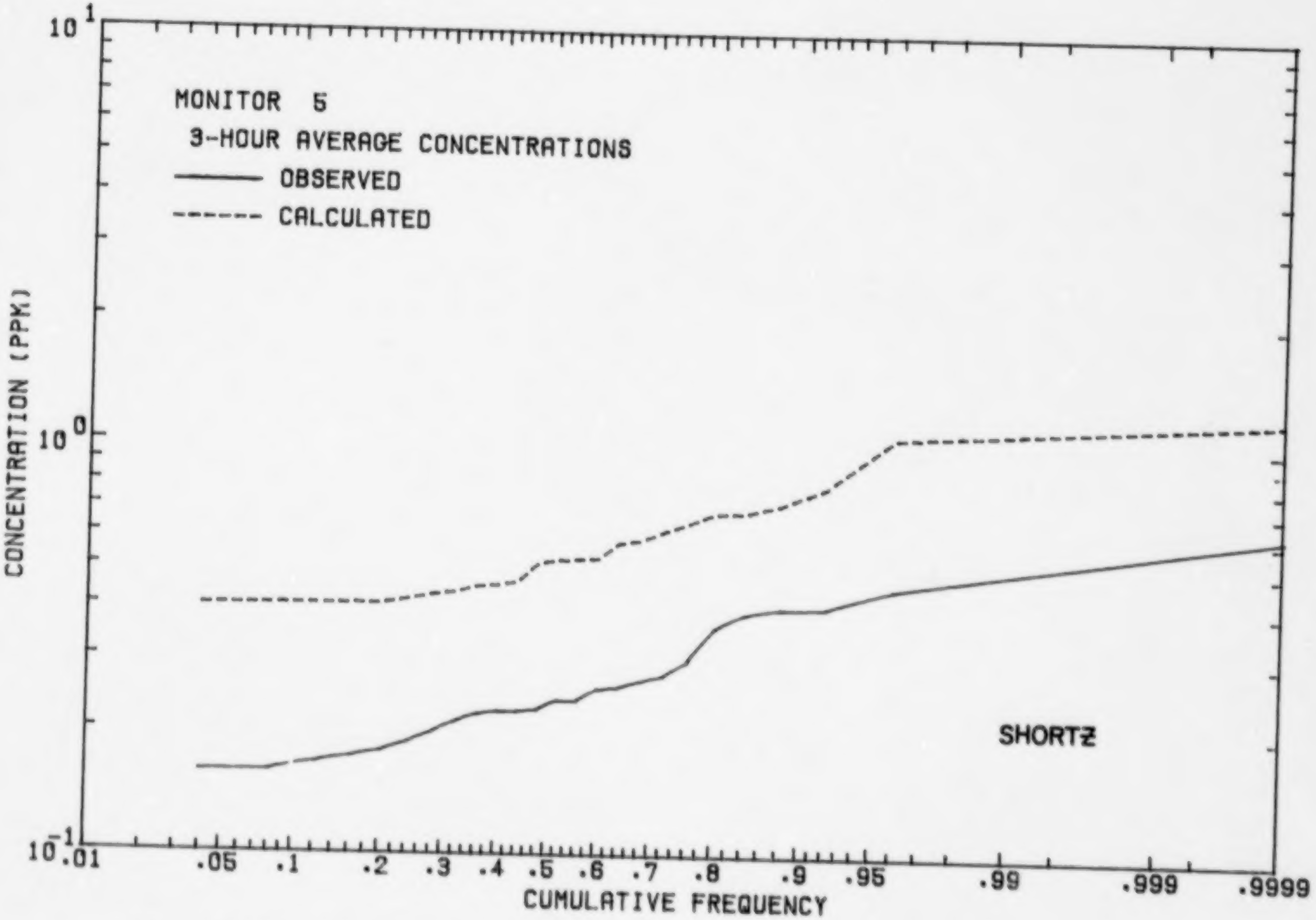

Figure D-11. Comparison of the cumulative frequency distribution of the 25 highest observed (minus background) 3-hour average SO_2 concentrations at Monitor 5 during the second year of the Westvaco monitoring program with the cumulative frequency distribution of the 25 highest 3-hour average concentrations calculated by SHORTZ.

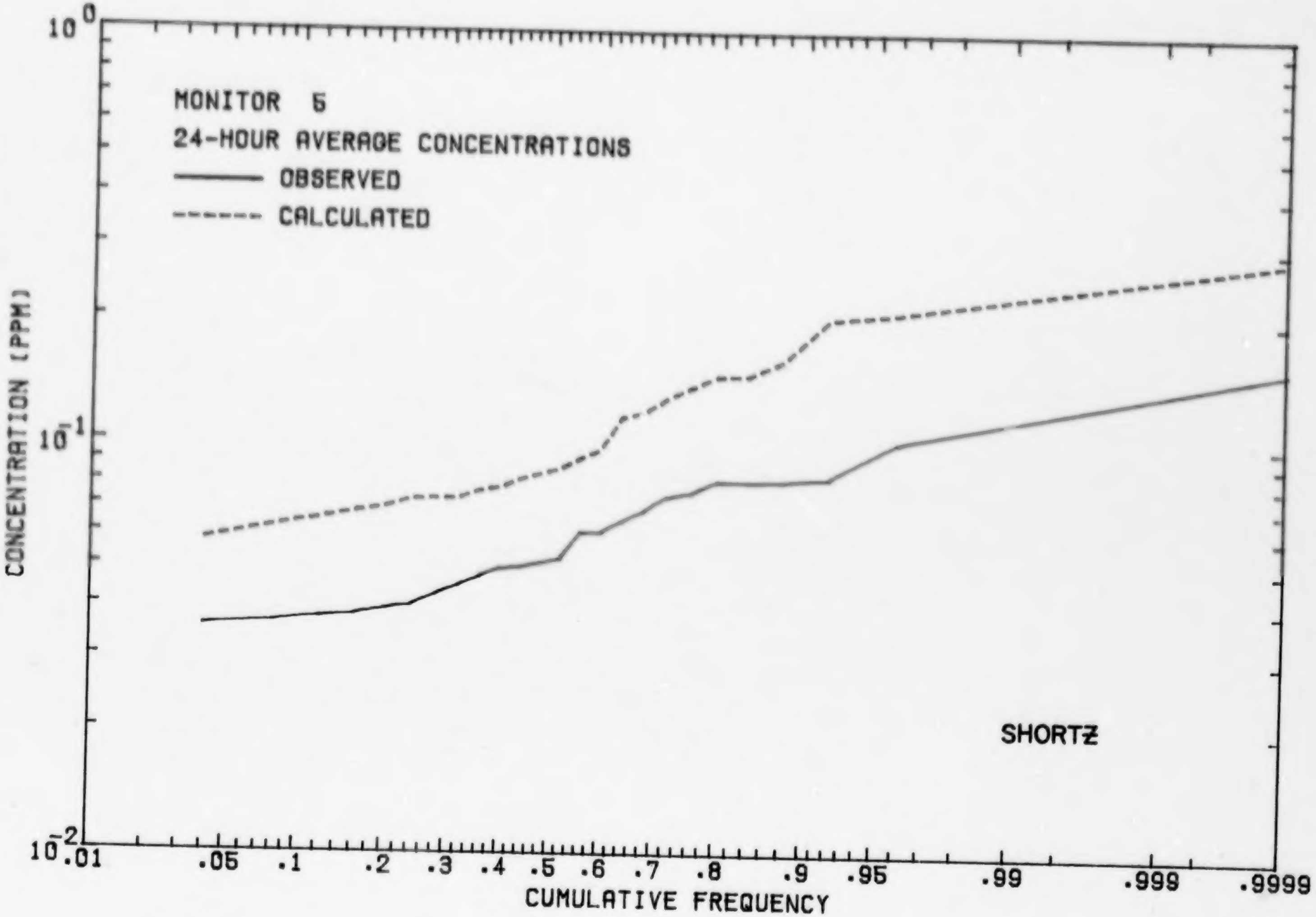

Figure D-12. Comparison of the cumulative frequency distribution of the 25 highest observed (minus background) 24-hour average SO_2 concentrations at Monitor 5 during the second year of the Westvaco monitoring program with the cumulative frequency distribution of the 25 highest 24-hour average concentrations calculated by SHORTZ.

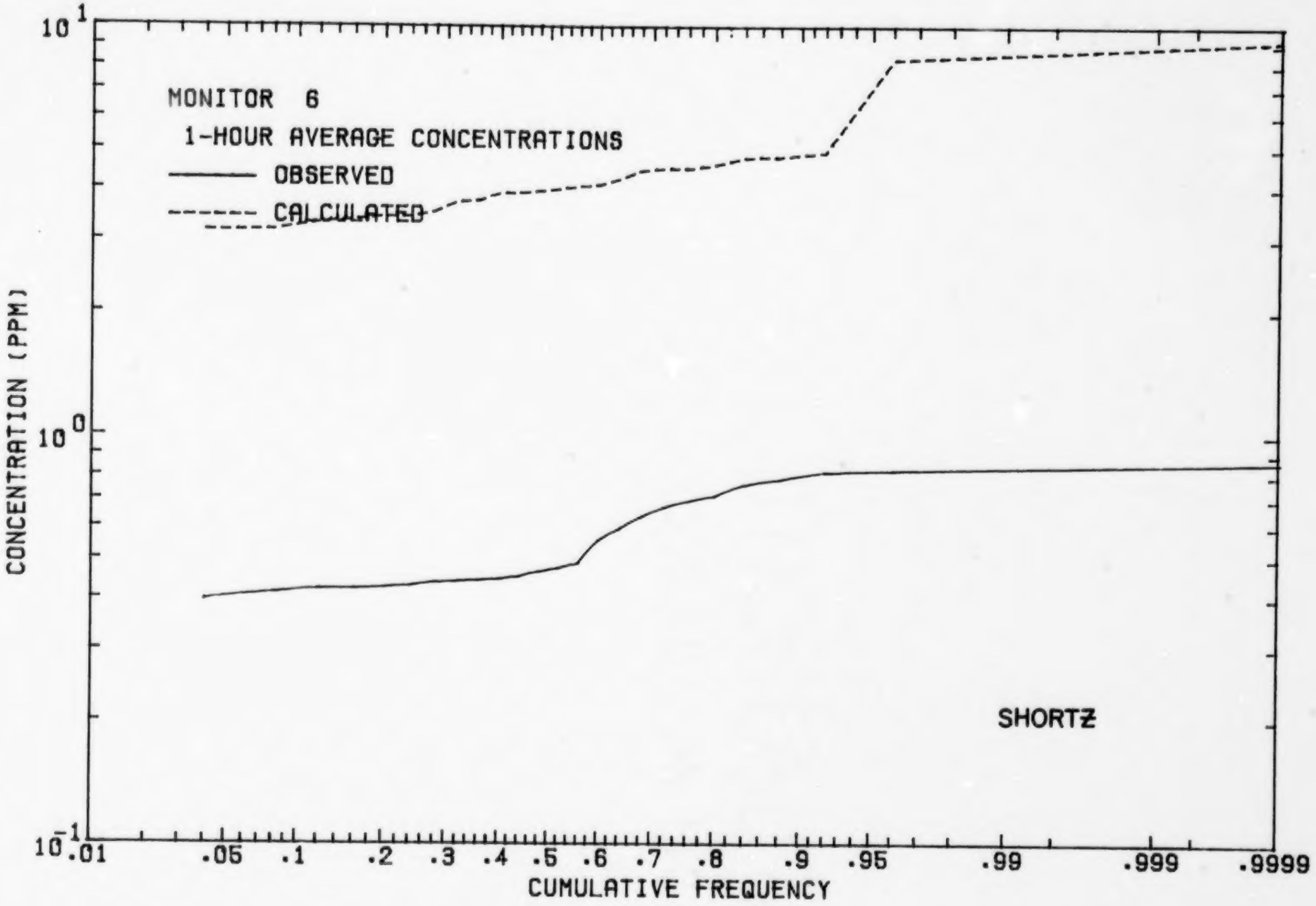

Figure D-13. Comparison of the cumulative frequency distribution of the 25 highest observed (minus background) 1-hour average SO_2 concentrations at Monitor 6 during the second year of the Westvaco monitoring program with the cumulative frequency distribution of the 25 highest 1-hour average concentrations calculated by SHORTZ.

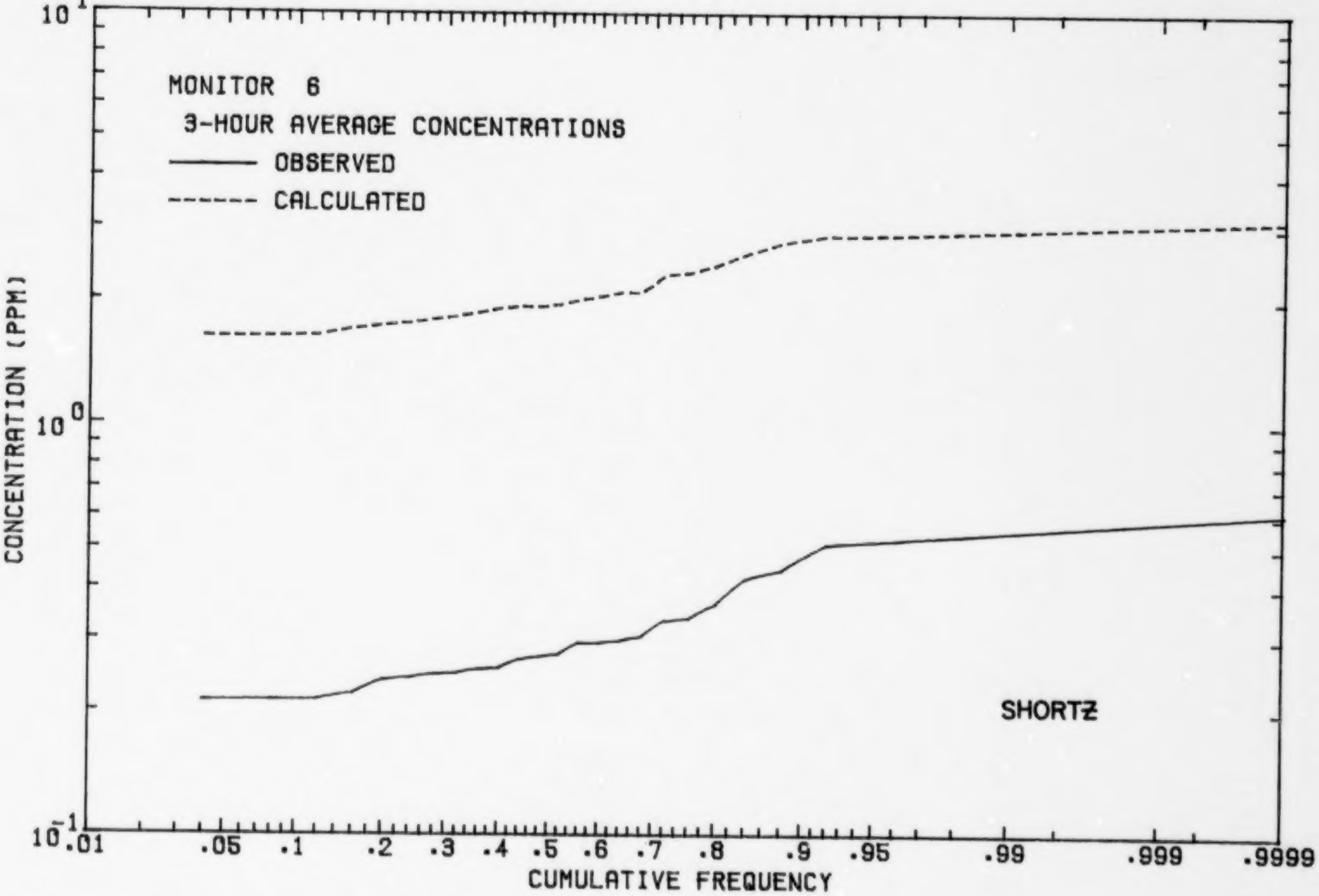

Figure D-14. Comparison of the cumulative frequency distribution of the 25 highest observed (minus background) 3-hour average SO_2 concentrations at Monitor 6 during the second year of the Westvaco monitoring program with the cumulative frequency distribution of the 25 highest 3-hour average concentrations calculated by SHORTZ.

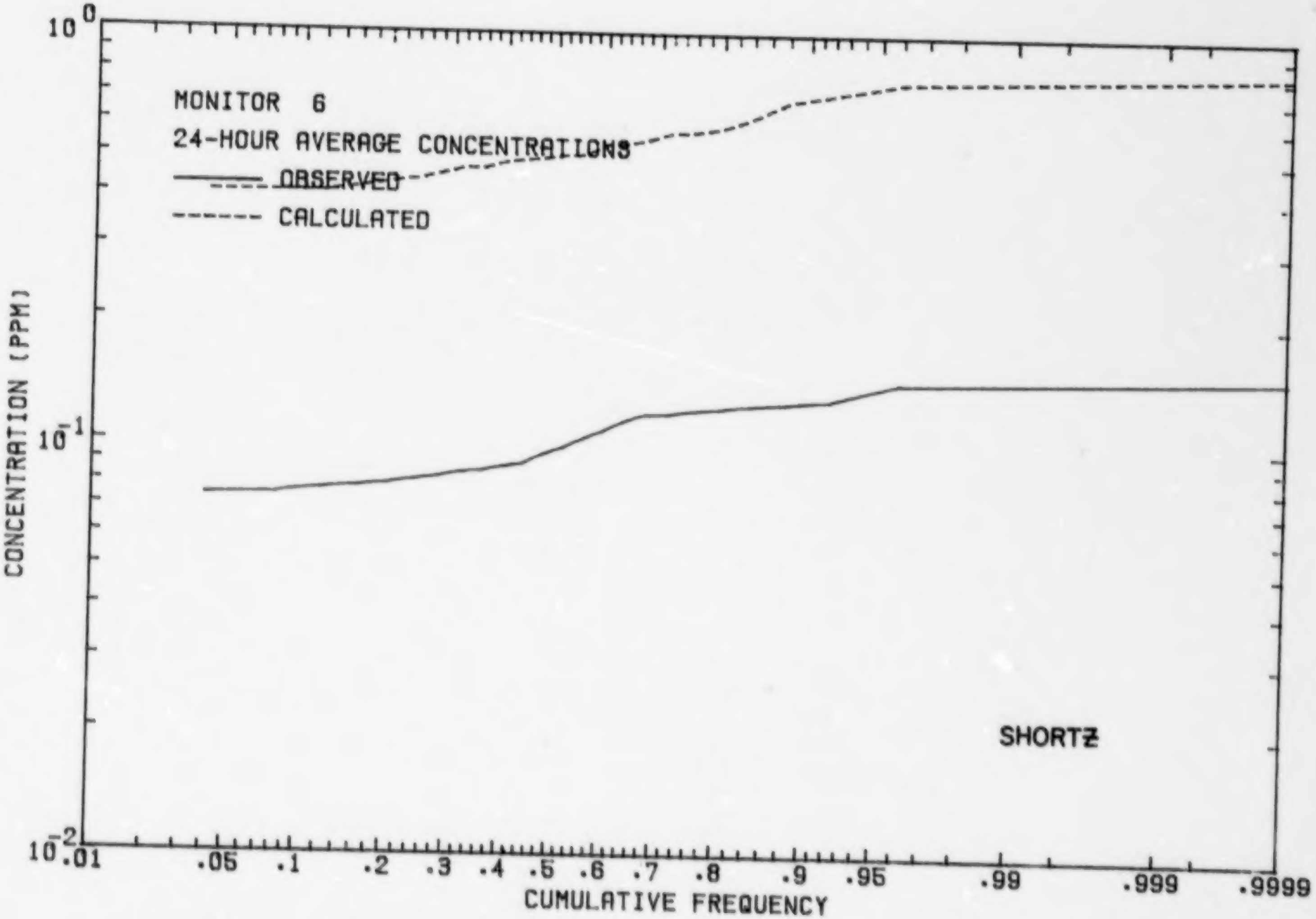

Figure D-15. Comparison of the cumulative frequency distribution of the 25 highest observed (minus background) 24-hour average SO_2 concentrations at Monitor 6 during the second year of the Westvaco monitoring program with the cumulative frequency distribution of the 25 highest 24-hour average concentrations calculated by SHORTZ.

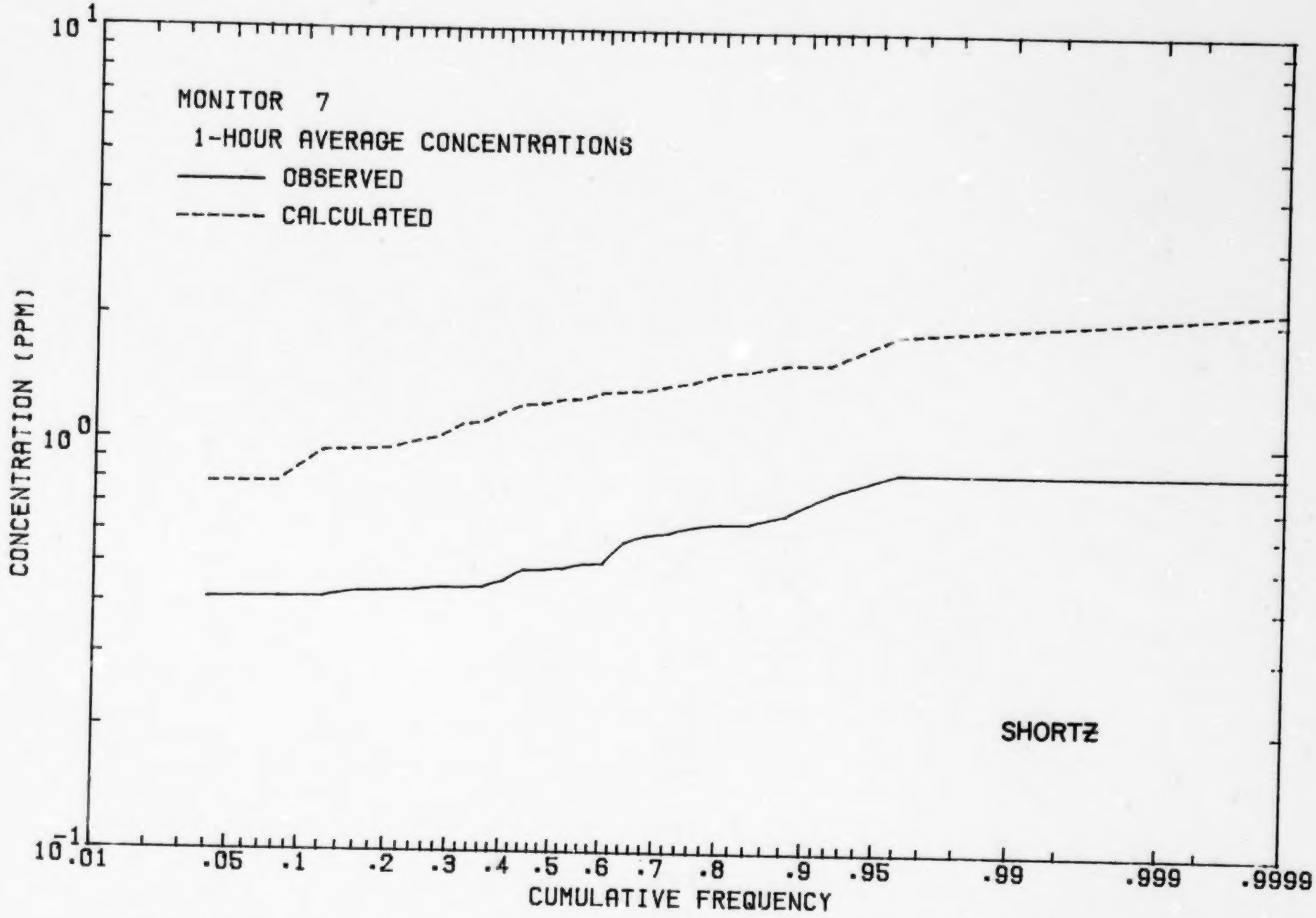

Figure D-16. Comparison of the cumulative frequency distribution of the 25 highest observed (minus background) 1-hour average SO_2 concentrations at Monitor 7 during the second year of the Westvaco monitoring program with the cumulative frequency distribution of the 25 highest 1-hour average concentrations calculated by SHORTZ.

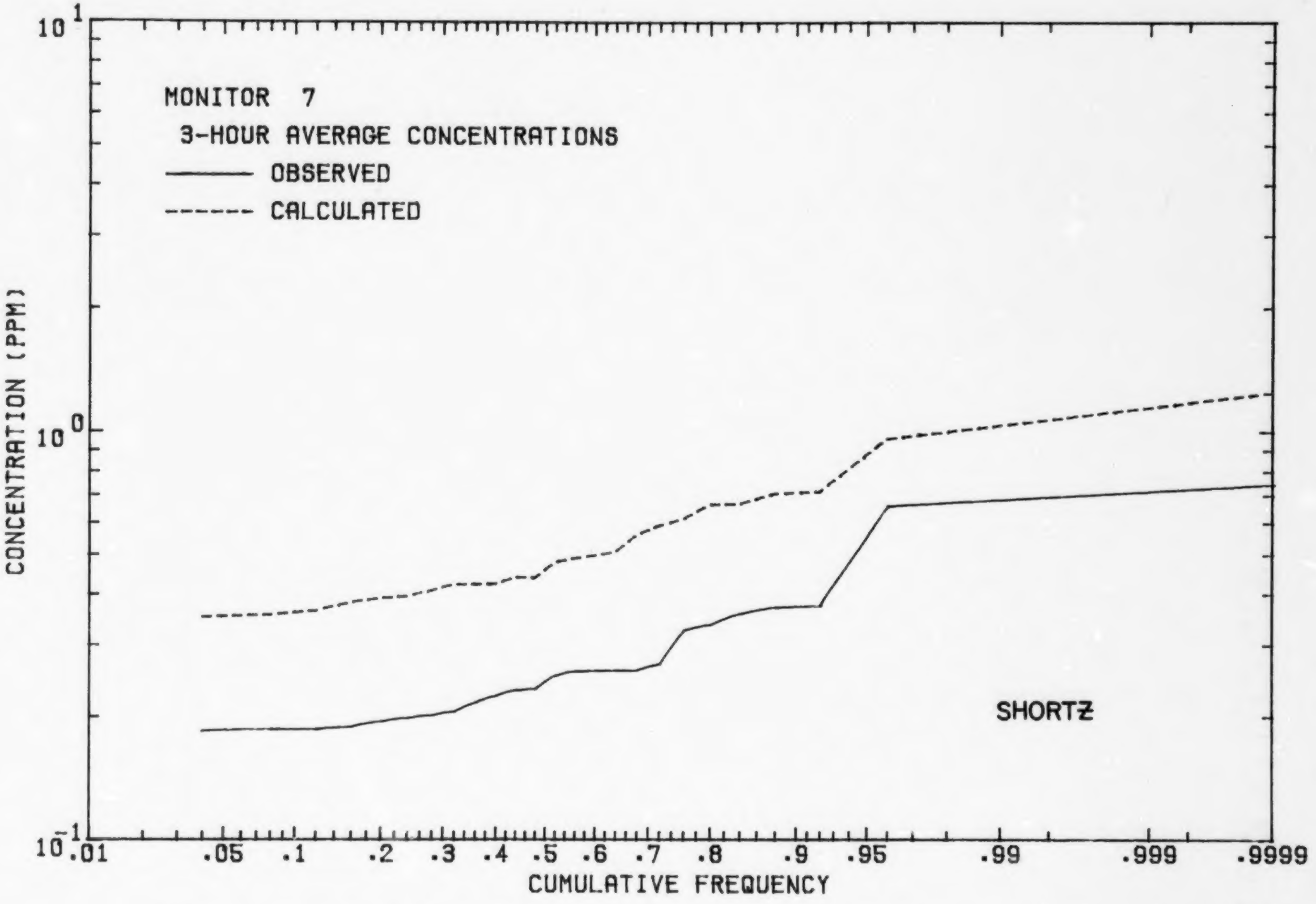

Figure D-17. Comparison of the cumulative frequency distribution of the 25 highest observed (minus background) 3-hour average SO_2 concentrations at Monitor 7 during the second year of the Westvaco monitoring program with the cumulative frequency distribution of the 25 highest 3-hour average concentrations calculated by SHORTZ.

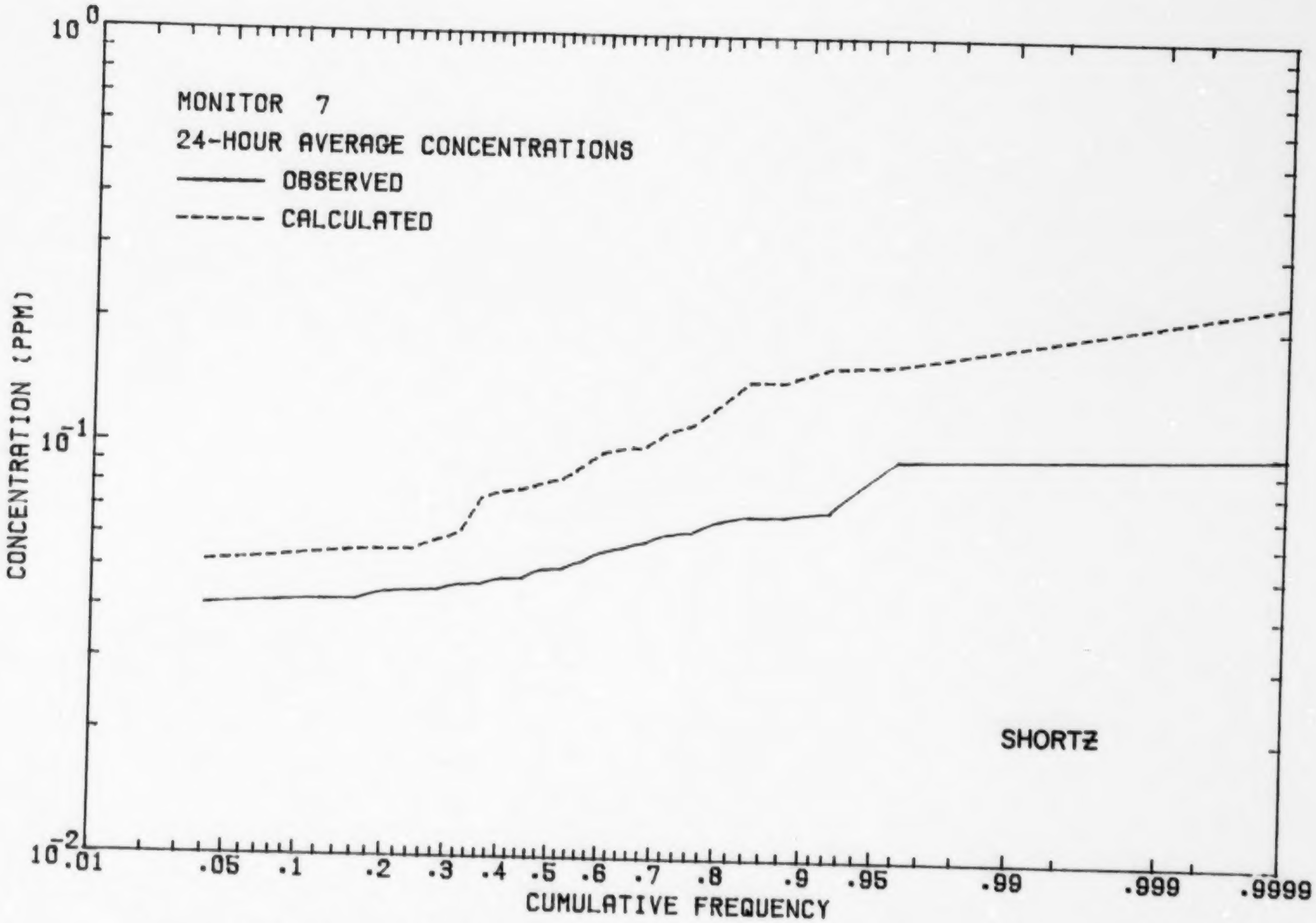

Figure D-18. Comparison of the cumulative frequency distribution of the 25 highest observed (minus background) 24-hour average SO_2 concentrations at Monitor 7 during the second year of the Westvaco monitoring program with the cumulative frequency distribution of the 25 highest 24-hour average concentrations calculated by SHORTZ.

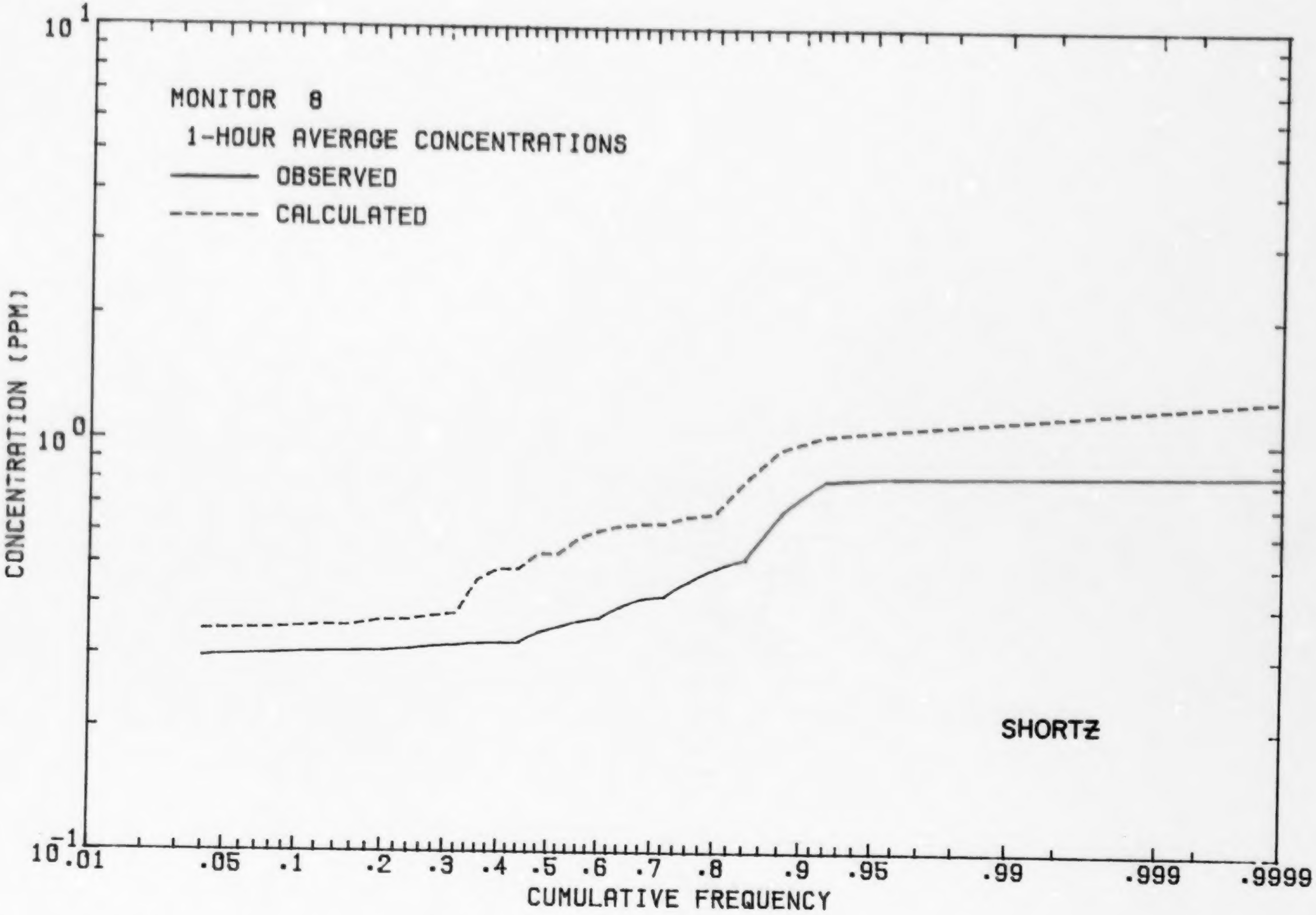

Figure D-19. Comparison of the cumulative frequency distribution of the 25 highest observed (minus background) 1-hour average SO_2 concentrations at Monitor 8 during the second year of the Westvaco monitoring program with the cumulative frequency distribution of the 25 highest 1-hour average concentrations calculated by SHORTZ.

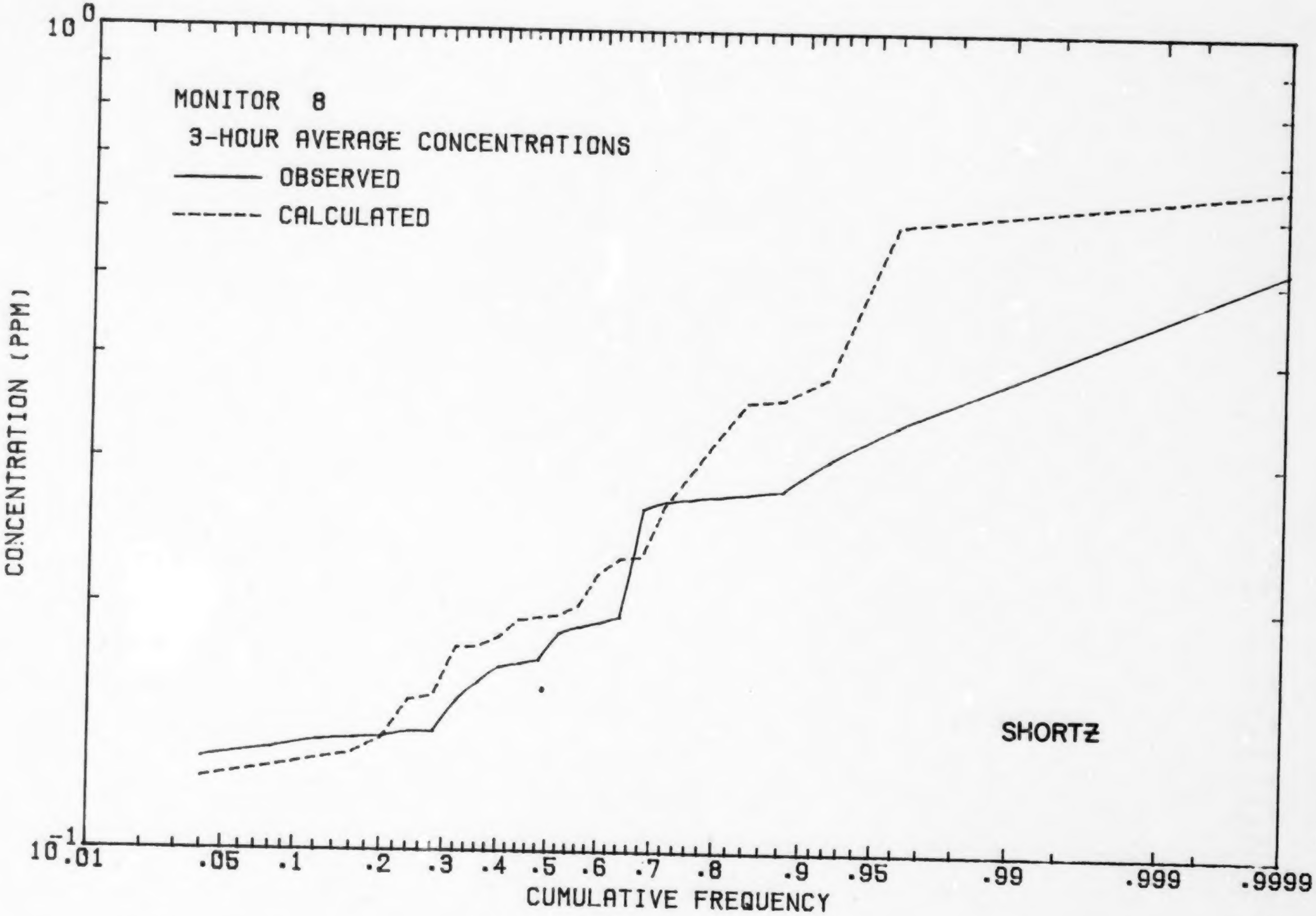

Figure D-20. Comparison of the cumulative frequency distribution of the 25 highest observed (minus background) 3-hour average SO_2 concentrations at Monitor 8 during the second year of the Westvaco monitoring program with the cumulative frequency distribution of the 25 highest 3-hour average concentrations calculated by SHORTZ.

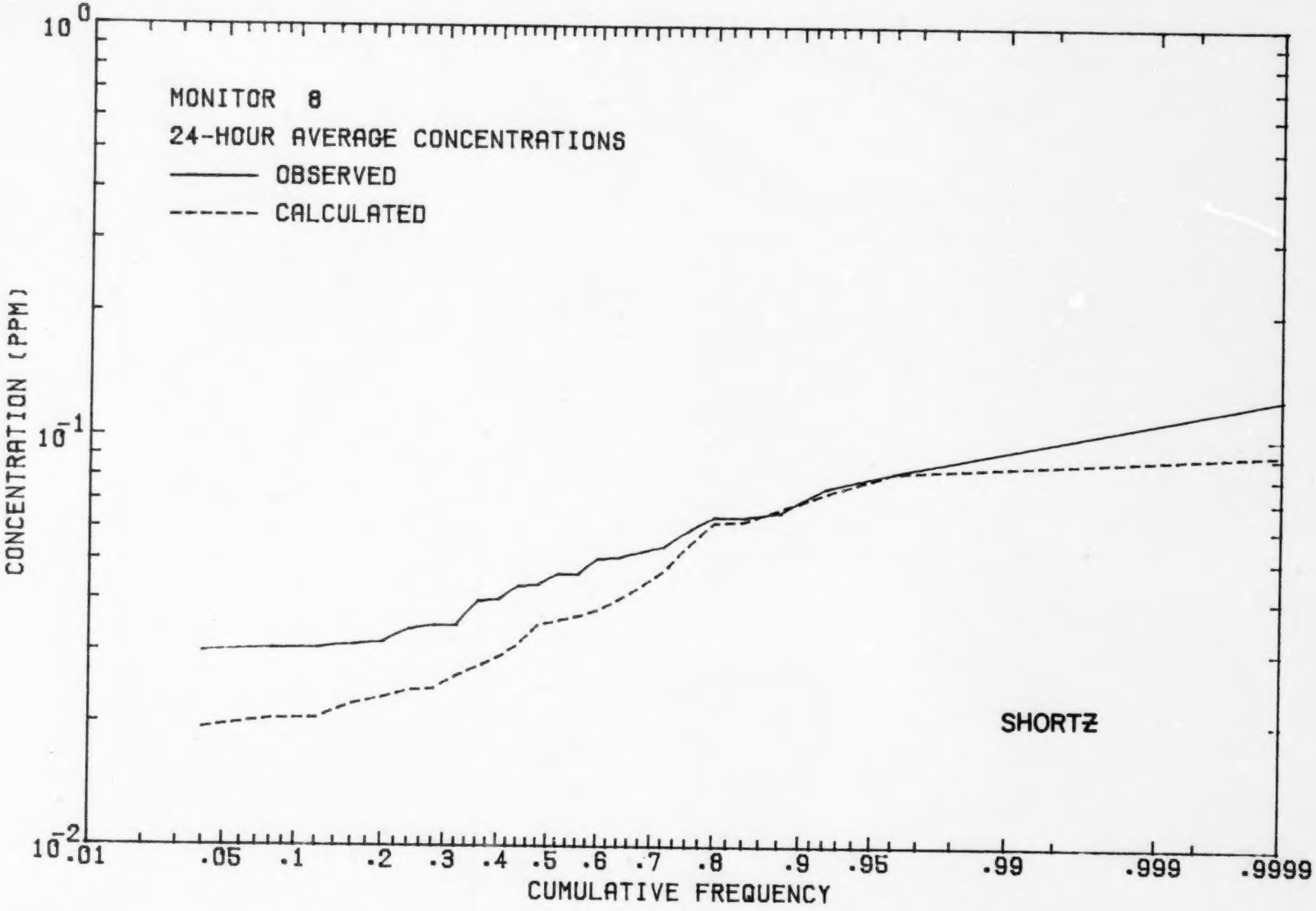

Figure D-21. Comparison of the cumulative frequency distribution of the 25 highest observed (minus background) 24-hour average SO_2 concentrations at Monitor 8 during the second year of the Westvaco monitoring program with the cumulative frequency distribution of the 25 highest 24-hour average concentrations calculated by SHORTZ.

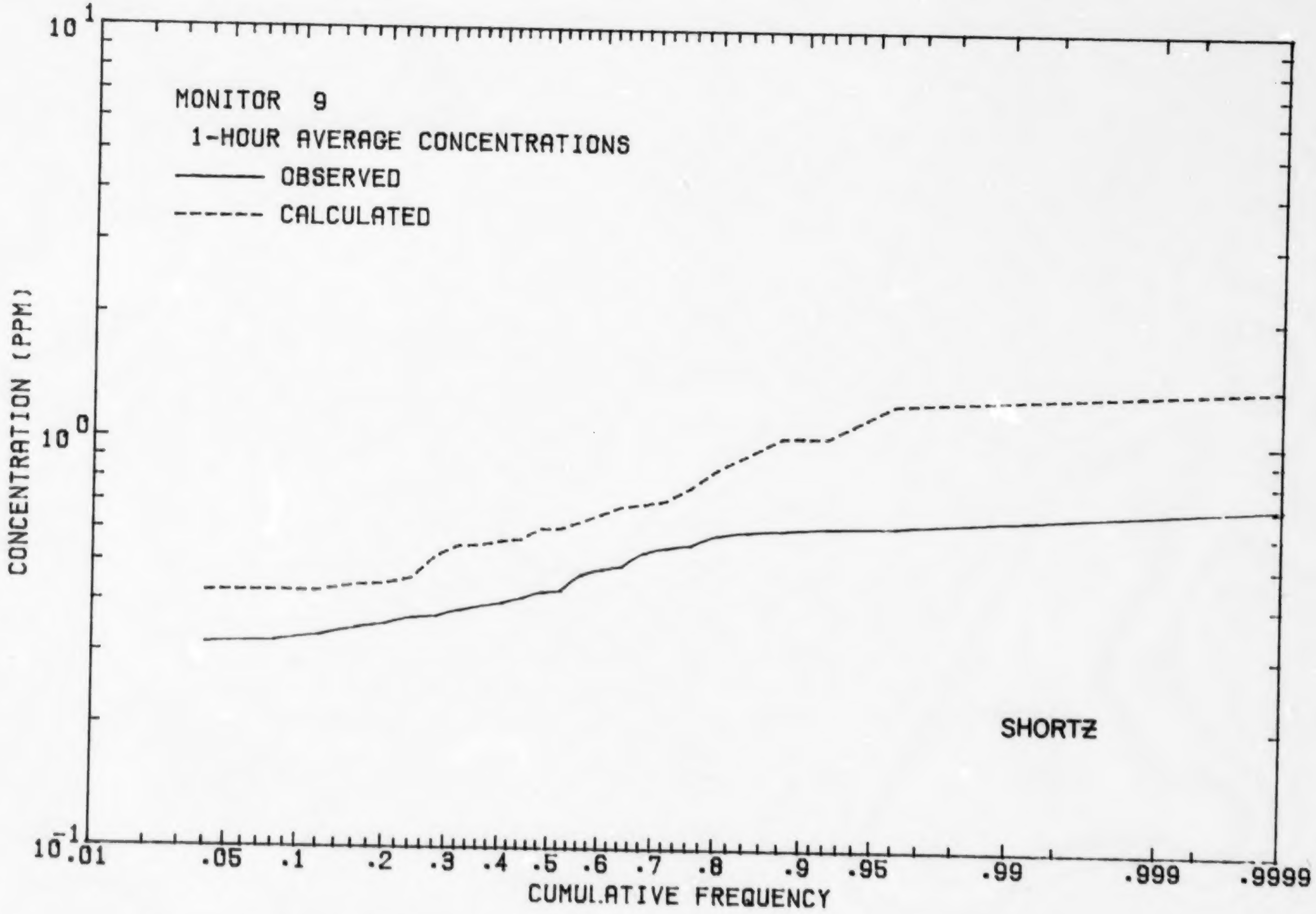

Figure D-22. Comparison of the cumulative frequency distribution of the 25 highest observed (minus background) 1-hour average SO_2 concentrations at Monitor 9 during the second year of the Westvaco monitoring program with the cumulative frequency distribution of the 25 highest 1-hour average concentrations calculated by SHORTZ.

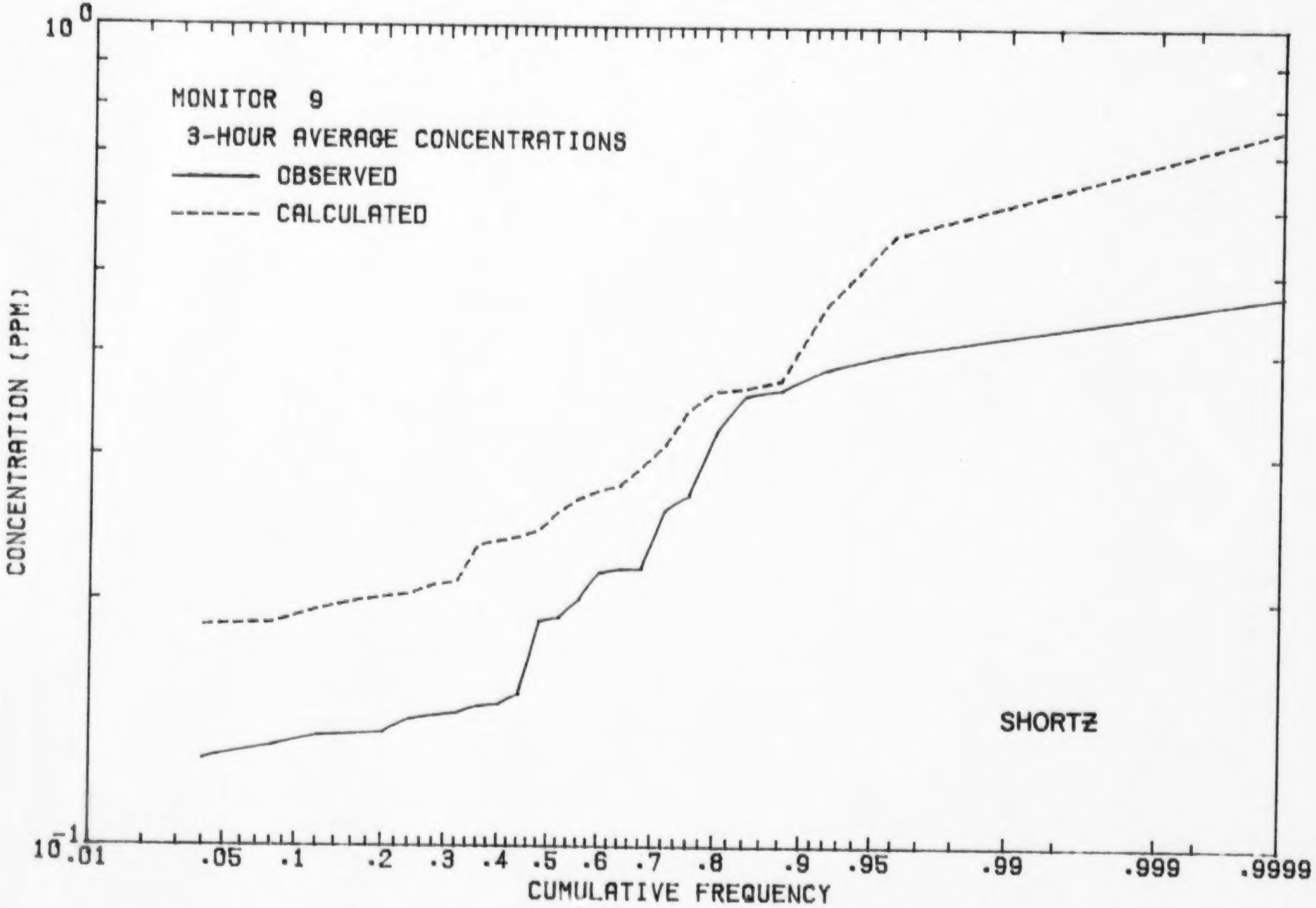

Figure D-23. Comparison of the cumulative frequency distribution of the 25 highest observed (minus background) 3-hour average SO_2 concentrations at Monitor 9 during the second year of the Westvaco monitoring program with the cumulative frequency distribution of the 25 highest 3-hour average concentrations calculated by SHORTZ.

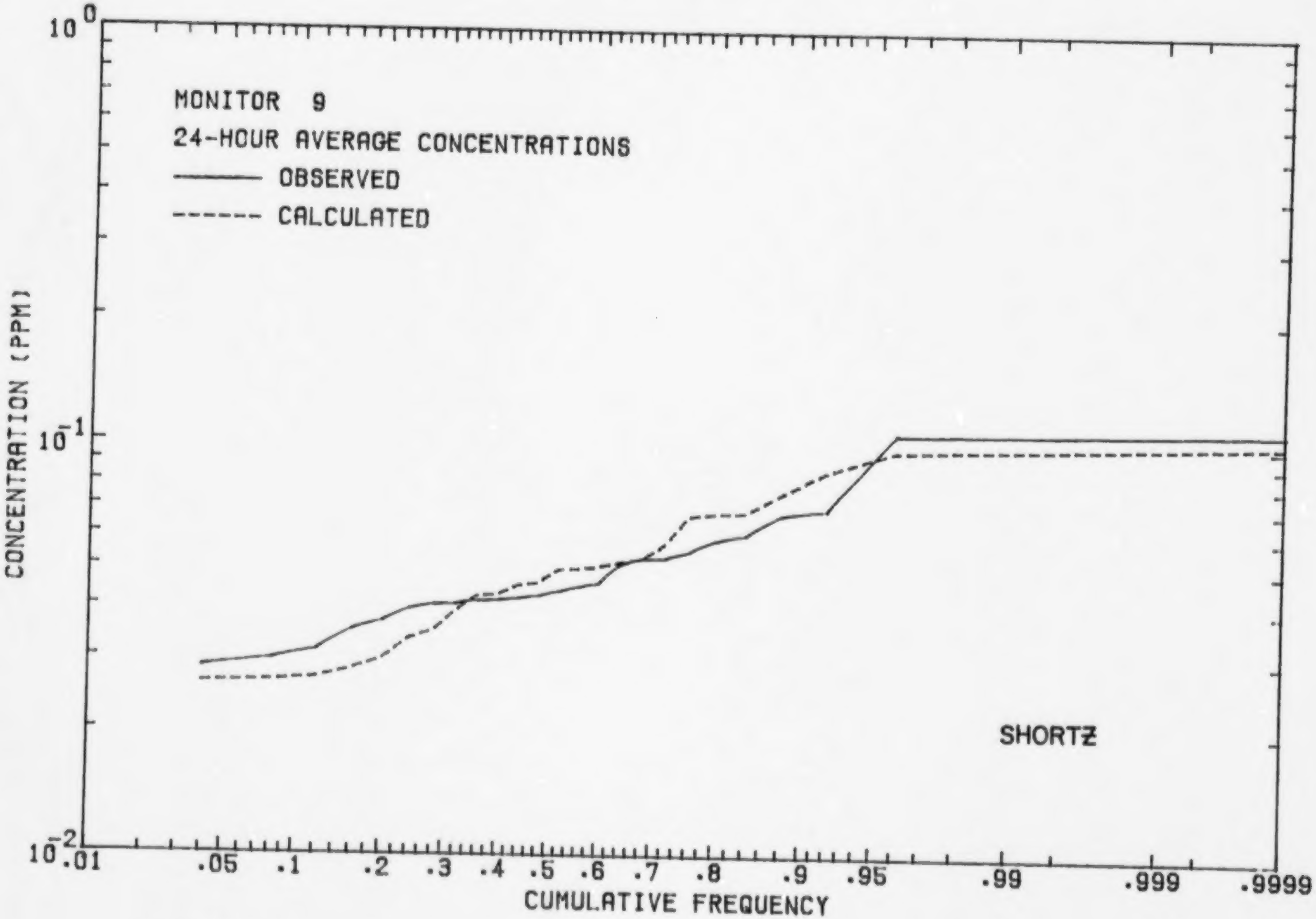

Figure D-24. Comparison of the cumulative frequency distribution of the 25 highest observed (minus background) 24-hour average SO_2 concentrations at Monitor 9 during the second year of the Westvaco monitoring program with the cumulative frequency distribution of the 25 highest 24-hour average concentrations calculated by SHORTZ.

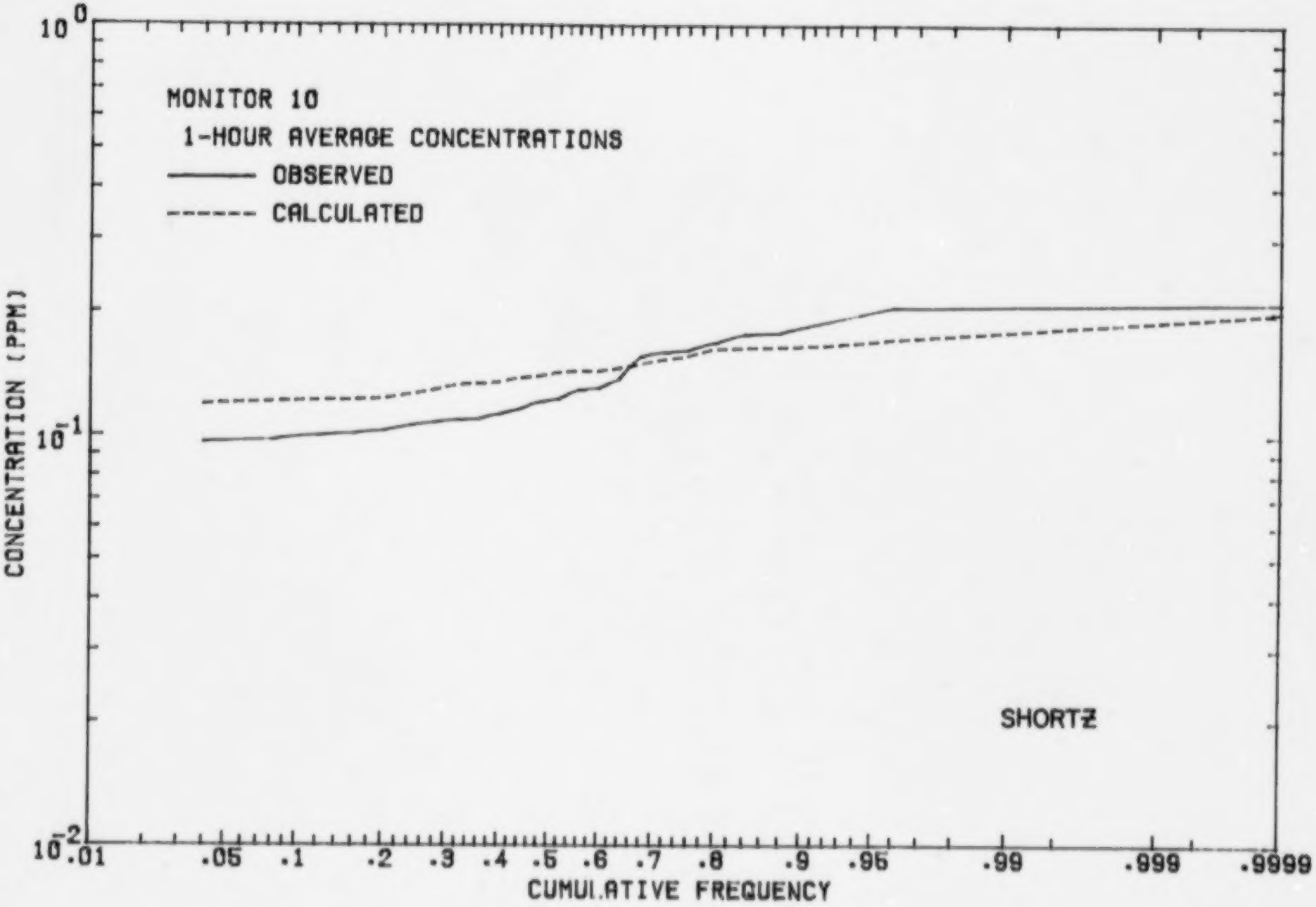

Figure D-25. Comparison of the cumulative frequency distribution of the 25 highest observed (minus background) 1-hour average SO_2 concentrations at Monitor 10 during the second year of the Westvaco monitoring program with the cumulative frequency distribution of the 25 highest 1-hour average concentrations calculated by SHORTZ.

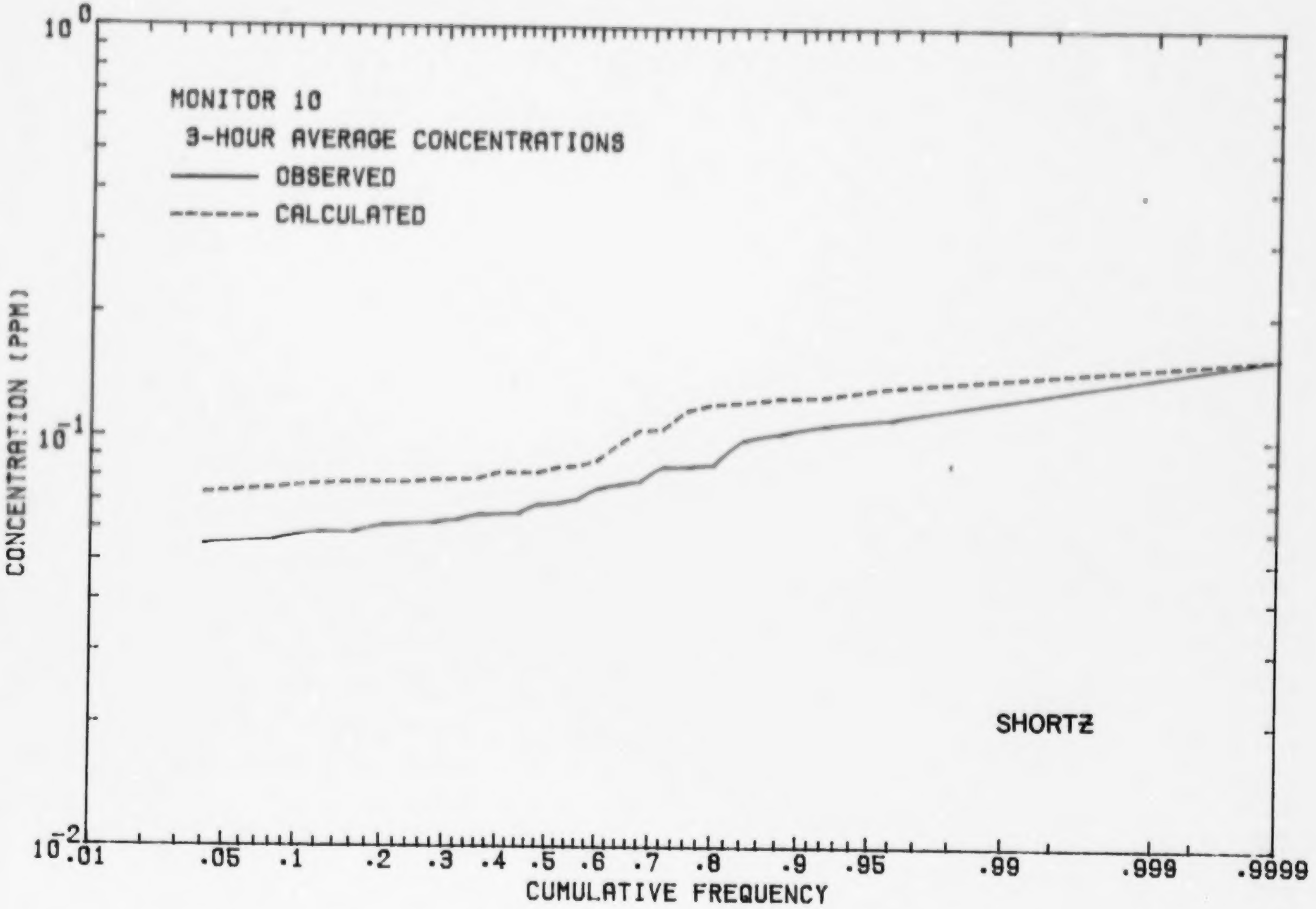

Figure D-26. Comparison of the cumulative frequency distribution of the 25 highest observed (minus background) 3-hour average SO_2 concentrations at Monitor 10 during the second year of the Westvaco monitoring program with the cumulative frequency distribution of the 25 highest 3-hour average concentrations calculated by SHORTZ.

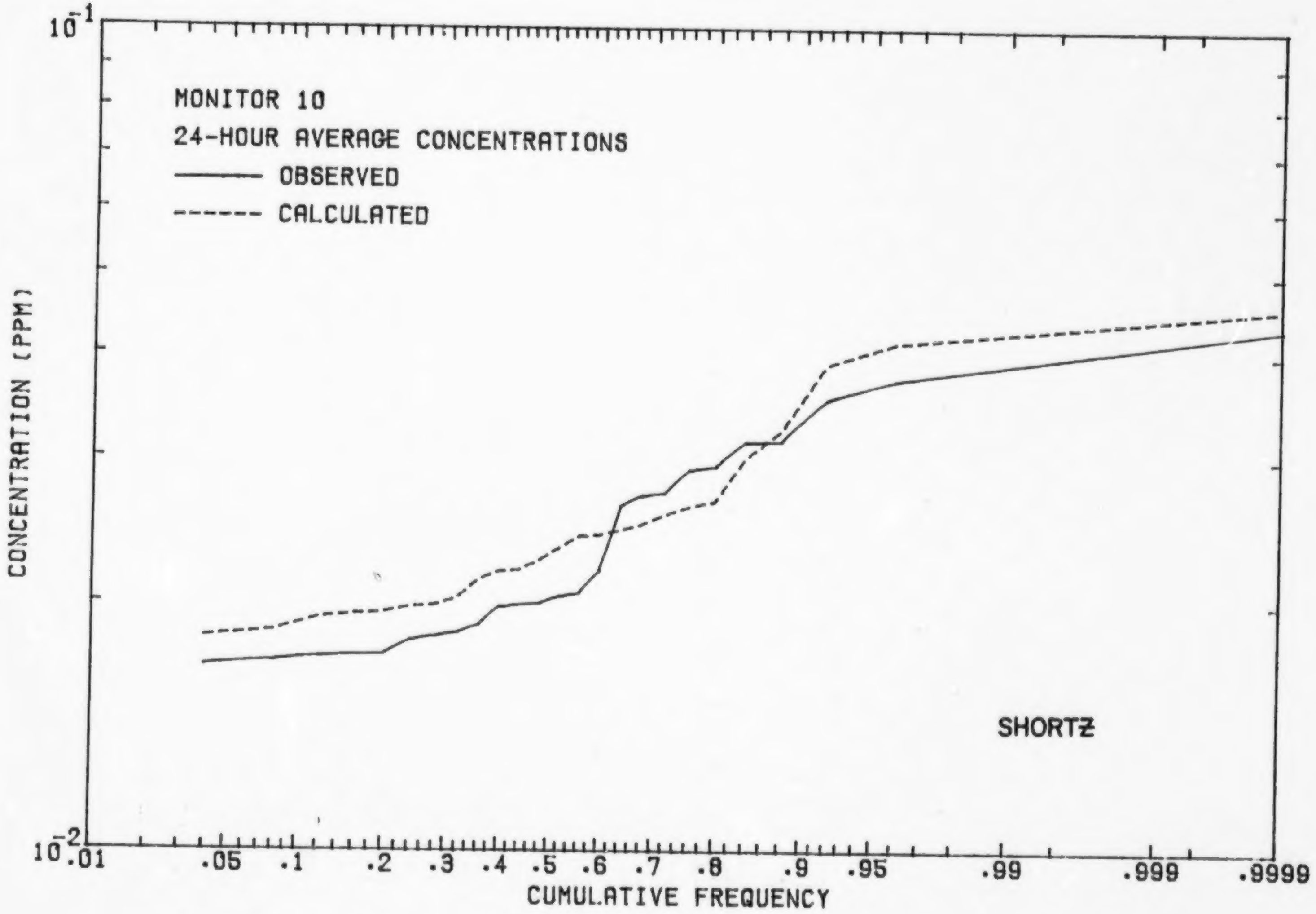

Figure D-27. Comparison of the cumulative frequency distribution of the 25 highest observed (minus background) 24-hour average SO_2 concentrations at Monitor 10 during the second year of the Westvaco monitoring program with the cumulative frequency distribution of the 25 highest 24-hour average concentrations calculated by SHORTZ.

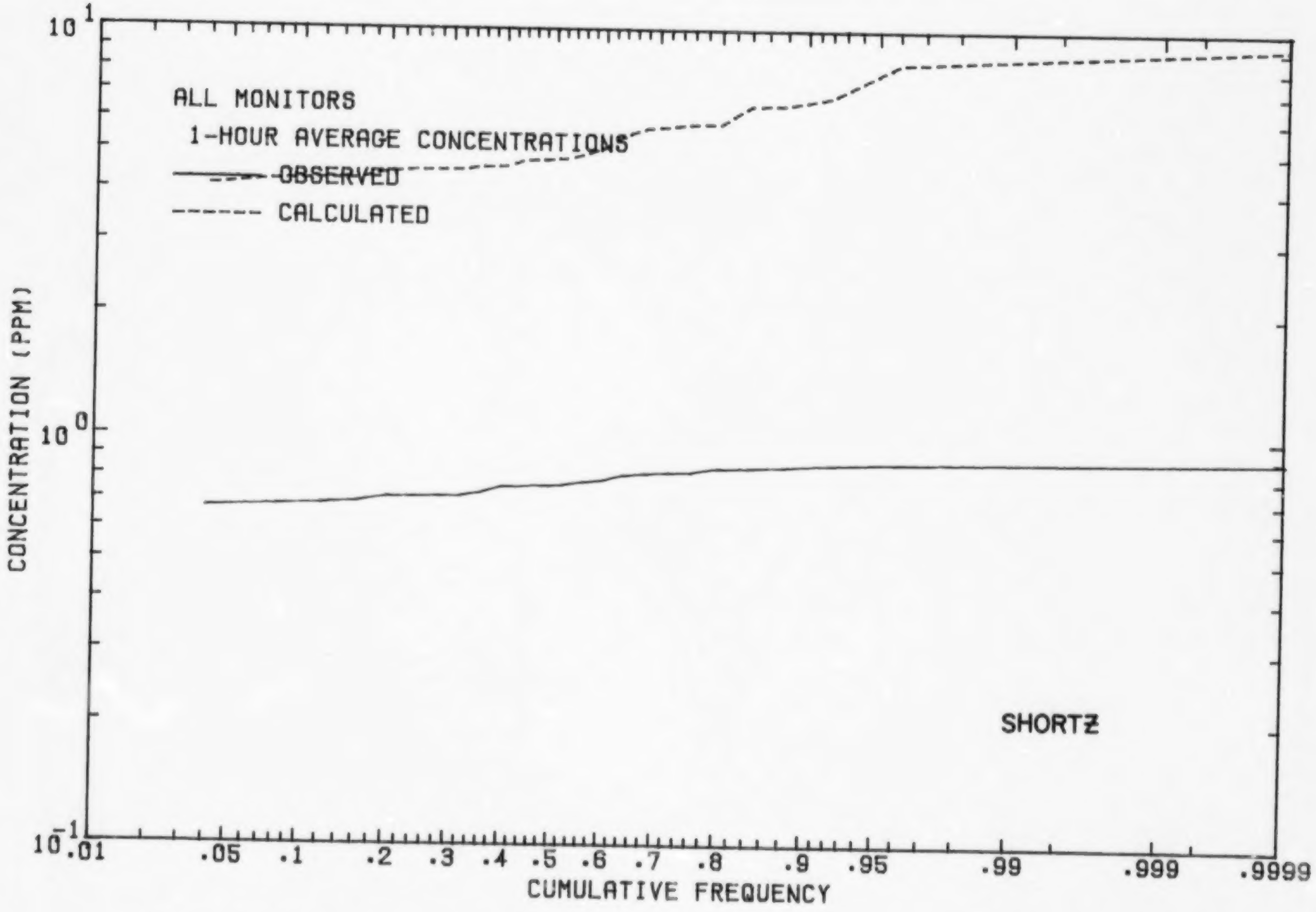

Figure D-28. Comparison of the cumulative frequency distribution of the 25 highest observed (minus background) 1-hour average SO_2 concentrations at all monitors during the second year of the Westvaco monitoring program with the cumulative frequency distribution of the 25 highest 1-hour average concentrations calculated by SHORTZ.

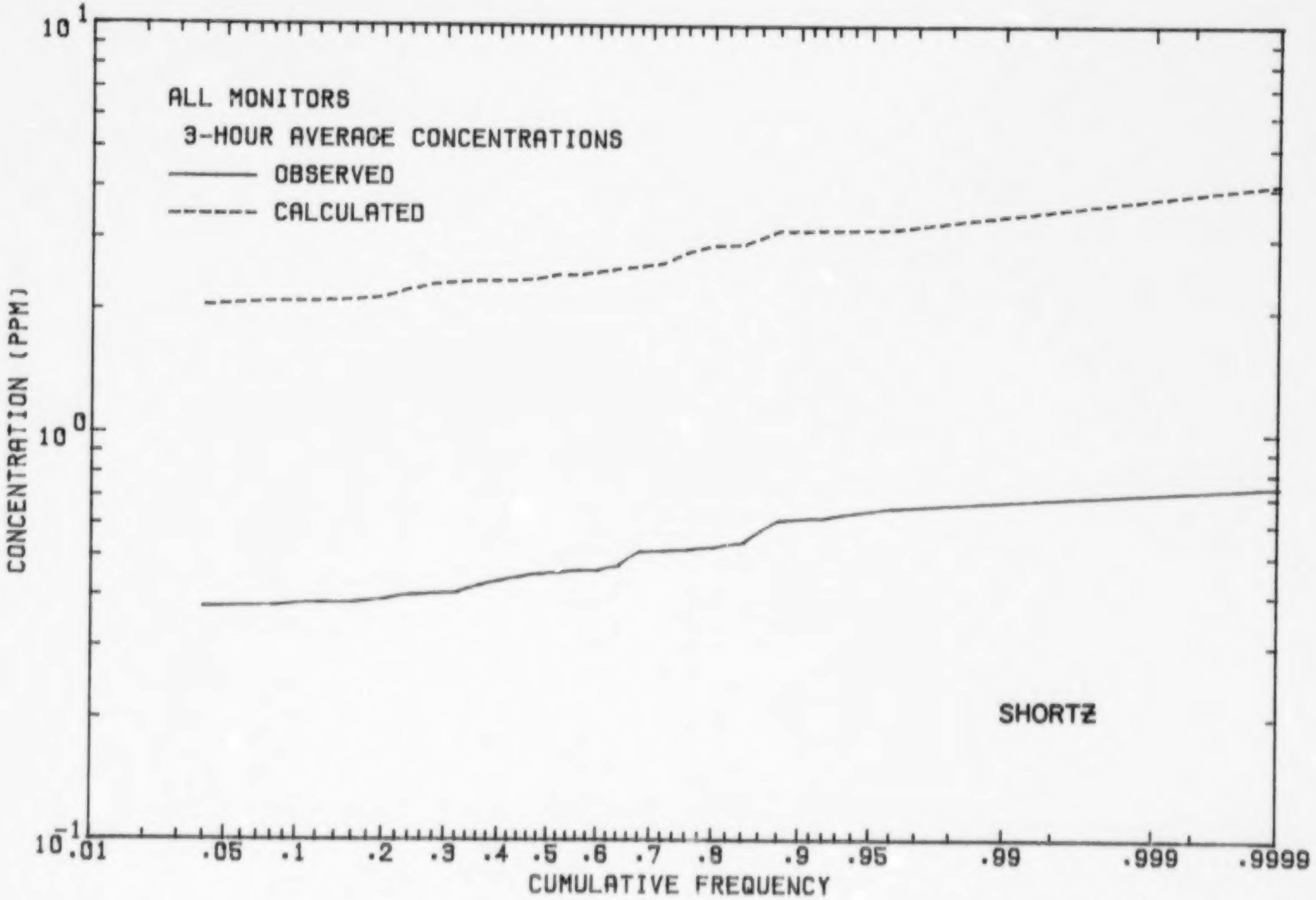

Figure D-29. Comparison of the cumulative frequency distribution of the 25 highest observed (minus background) 3-hour average SO_2 concentrations at all monitors during the second year of the Westvaco monitoring program with the cumulative frequency distribution of the 25 highest 3-hour average concentrations calculated by SHORTZ.

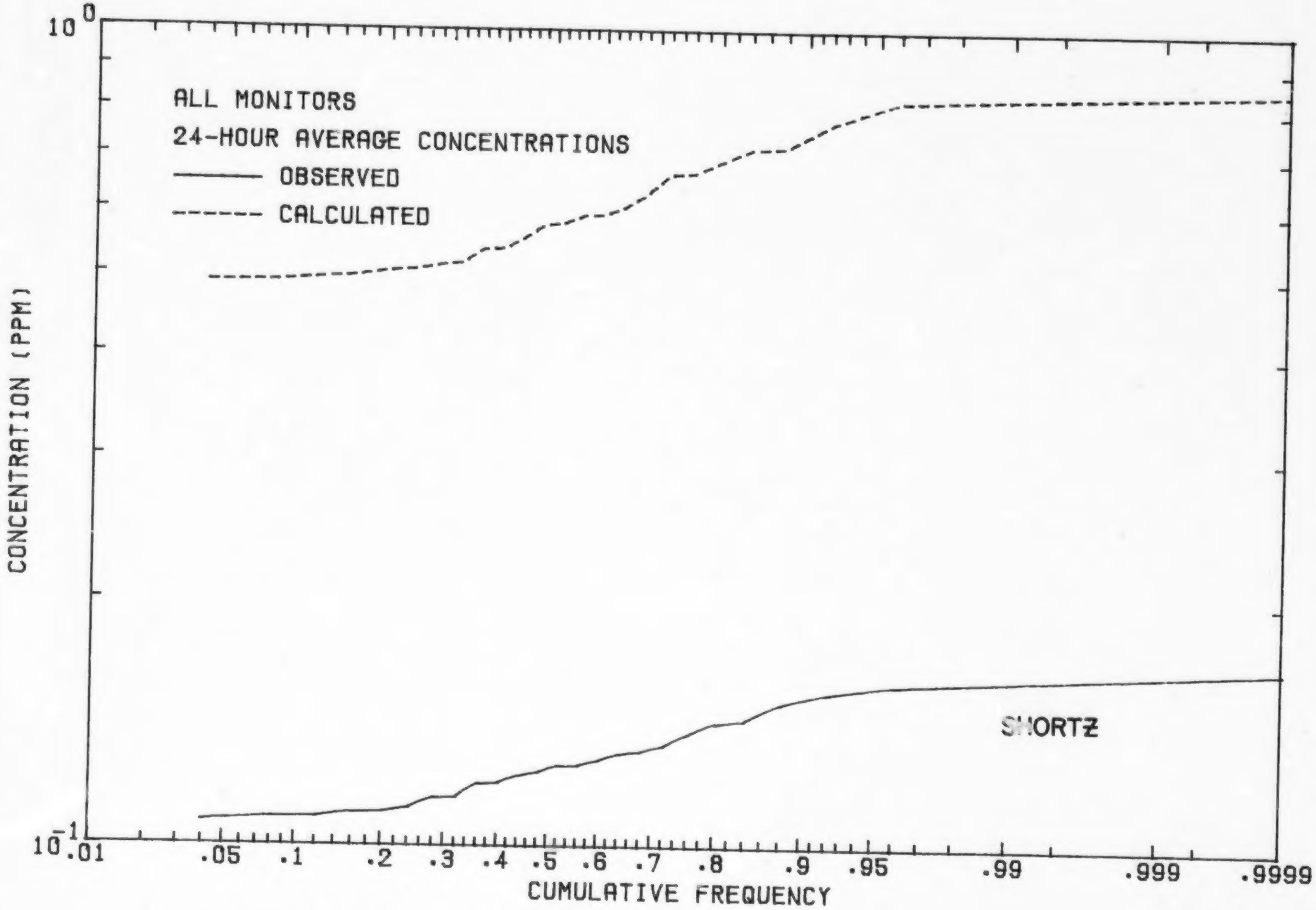

Figure D-30. Comparison of the cumulative frequency distribution of the 25 highest observed (minus background) 24-hour average SO_2 concentrations at all monitors during the second year of the Westvaco monitoring program with the cumulative frequency distribution of the 25 highest 24-hour average concentrations calculated by SHORTZ.

APPENDIX E

CUMULATIVE FREQUENCY DISTRIBUTIONS OF THE 25 HIGHEST OBSERVED (MINUS BACKGROUND) AND CALCULATED (LUMM) SHORT-TERM SO_2 CONCENTRATIONS

This appendix compares the cumulative frequency distributions of the 25 highest short-term (1-hour, 3-hour and 24-hour average) observed (minus background) and calculated (LUMM) SO_2 concentrations from Appendix A of the report by Hanna, et al. (1982b). Table E-1 gives the figure number for each combination of monitor and concentration averaging time. As noted in Section 3.2, the observed (minus background) 3-hour average SO_2 concentrations in this appendix are not necessarily the same as in Appendices B and D because 3-hour periods with 2 hours of valid concentration measurements were included by ERT in the determination of the 25 highest 3-hour average concentrations.

TABLE E-1

IDENTIFICATION OF FIGURE NUMBERS BY MONITOR AND CONCENTRATION AVERAGING TIME

Figure No.	Monitor	Averaging Time
E-1	1	1 Hour
E-2	1	3 Hours
E-3	1	24 Hours
E-4	3	1 Hour
E-5	3	3 Hours
E-6	3	24 Hours
E-7	4	1 Hour
E-8	4	3 Hours
E-9	4	24 Hours
E-10	5	1 Hour
E-11	5	3 Hours
E-12	5	24 Hours
E-13	6	1 Hour
E-14	6	3 Hours
E-15	6	24 Hours
E-16	7	1 Hour
E-17	7	3 Hours
E-18	7	24 Hours
E-19	8	1 Hour
E-20	8	3 Hours
E-21	8	24 Hours
E-22	9	1 Hour
E-23	9	3 Hours
E-24	9	24 Hours
E-25	10	1 Hour
E-26	10	3 Hours
E-27	10	24 Hours
E-28	All	1 Hour
E-29	All	3 Hours
E-30	All	24 Hours

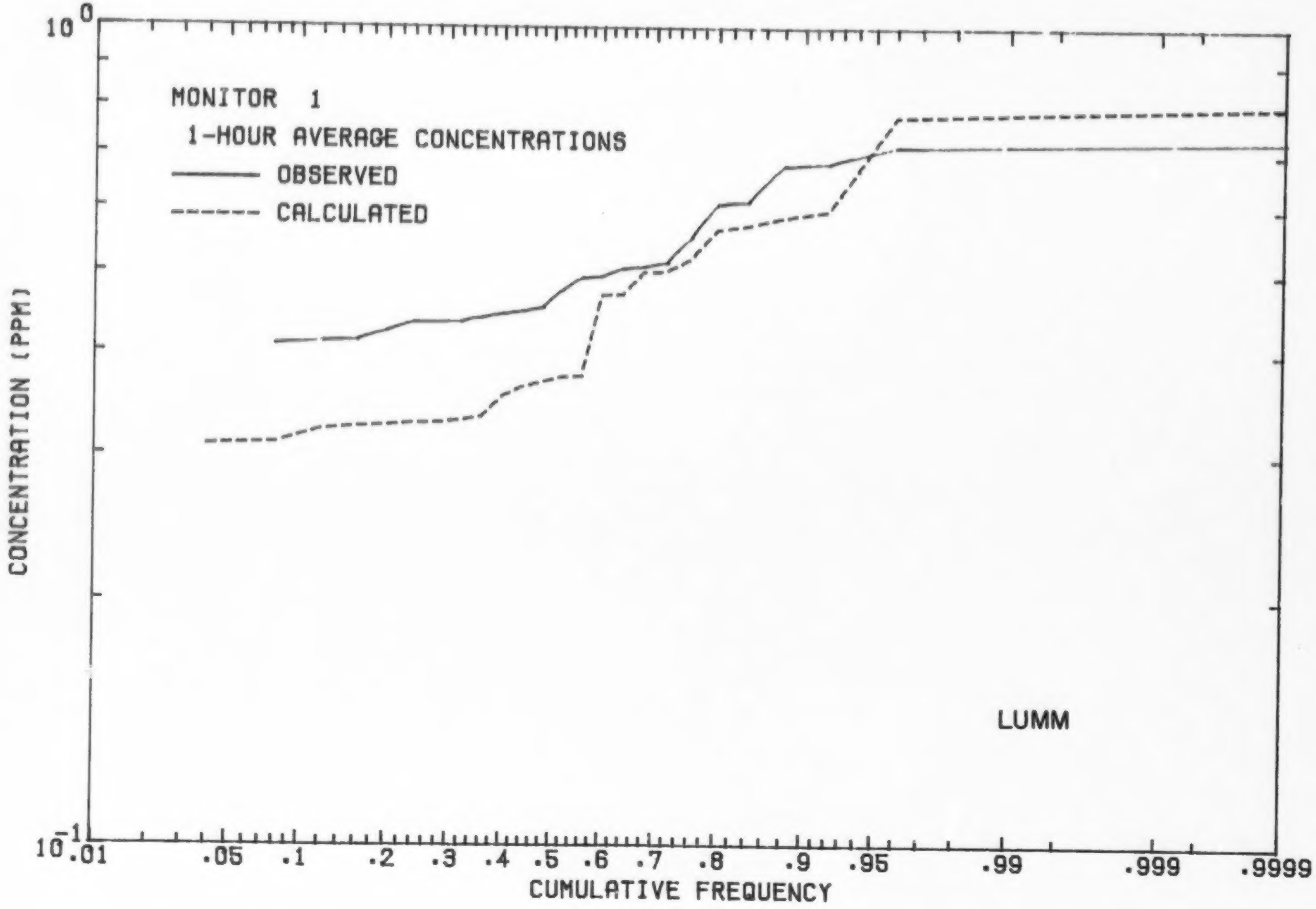

Figure E-1. Comparison of the cumulative frequency distribution of the 25 highest observed (minus background) 1-hour average SO_2 concentrations at Monitor 1 during the second year of the Westvaco monitoring program with the cumulative frequency distribution of the 25 highest 1-hour average concentrations calculated by LUMM.

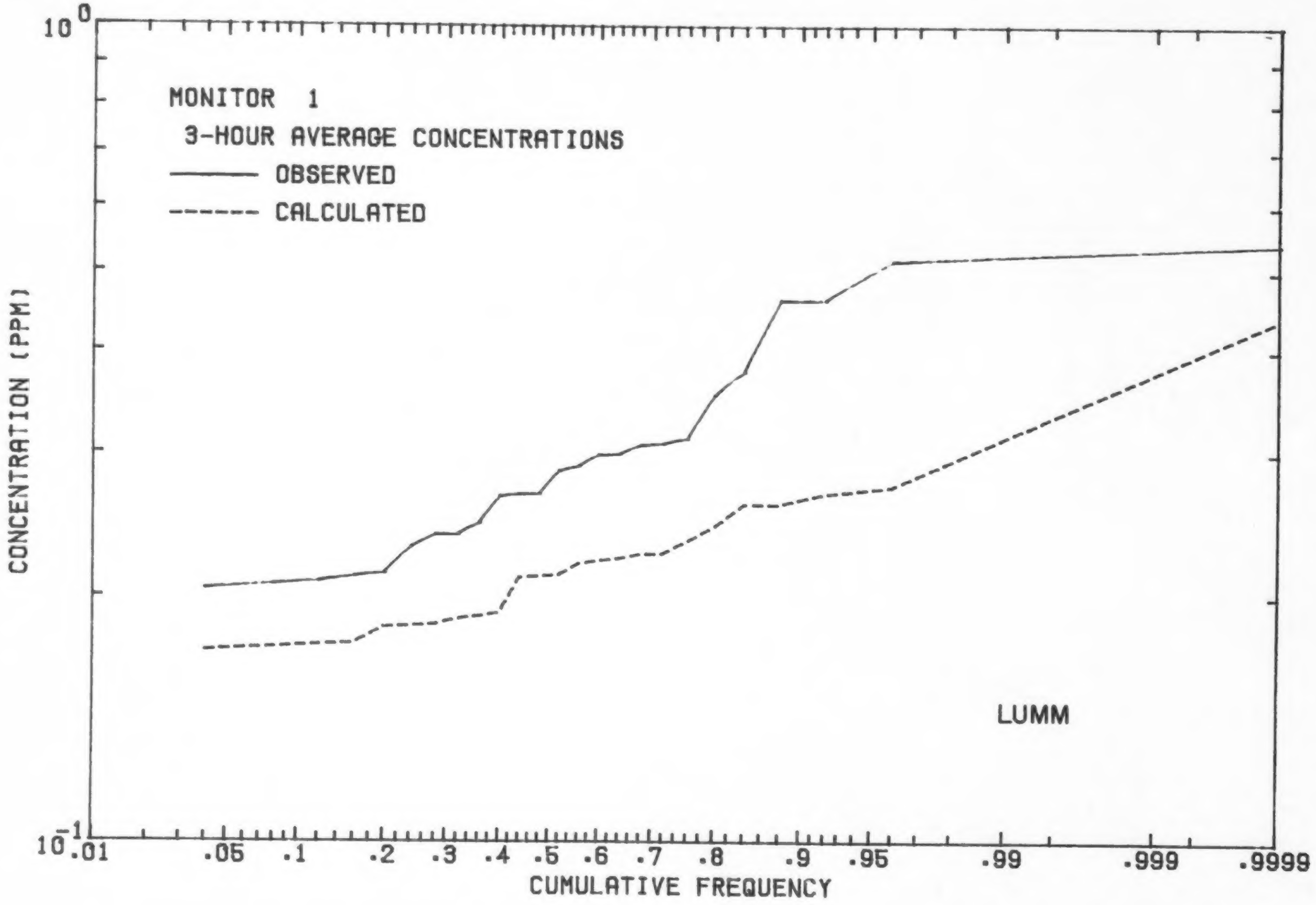

Figure E-2. Comparison of the cumulative frequency distribution of the 25 highest observed (minus background) 3-hour average SO_2 concentrations at Monitor 1 during the second year of the Westvaco monitoring program with the cumulative frequency distribution of the 25 highest 3-hour average concentrations calculated by LUMM.

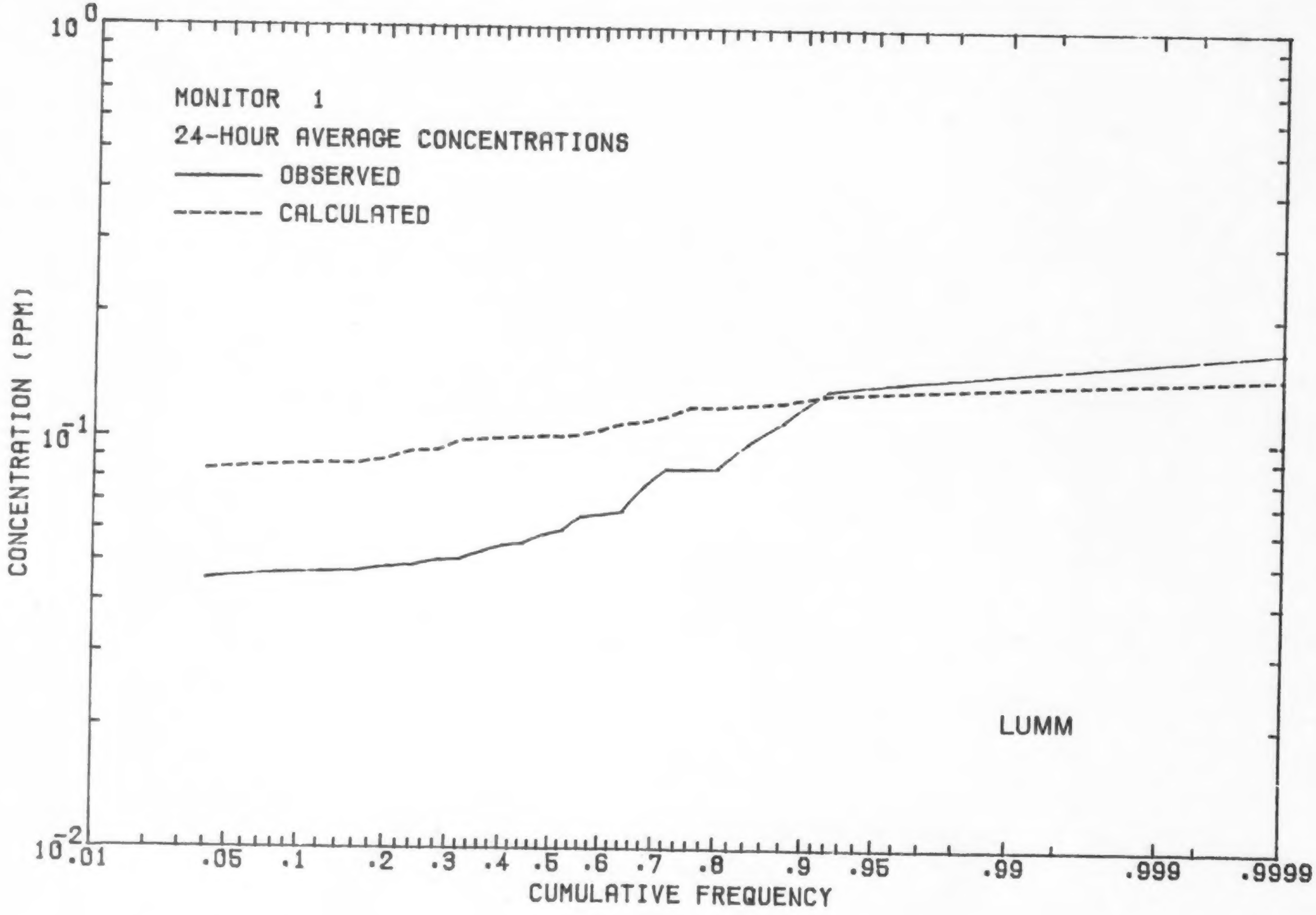

Figure E-3. Comparison of the cumulative frequency distribution of the 25 highest observed (minus background) 24-hour average SO_2 concentrations at Monitor 1 during the second year of the Westvaco monitoring program with the cumulative frequency distribution of the 25 highest 24-hour average concentrations calculated by LUMM.

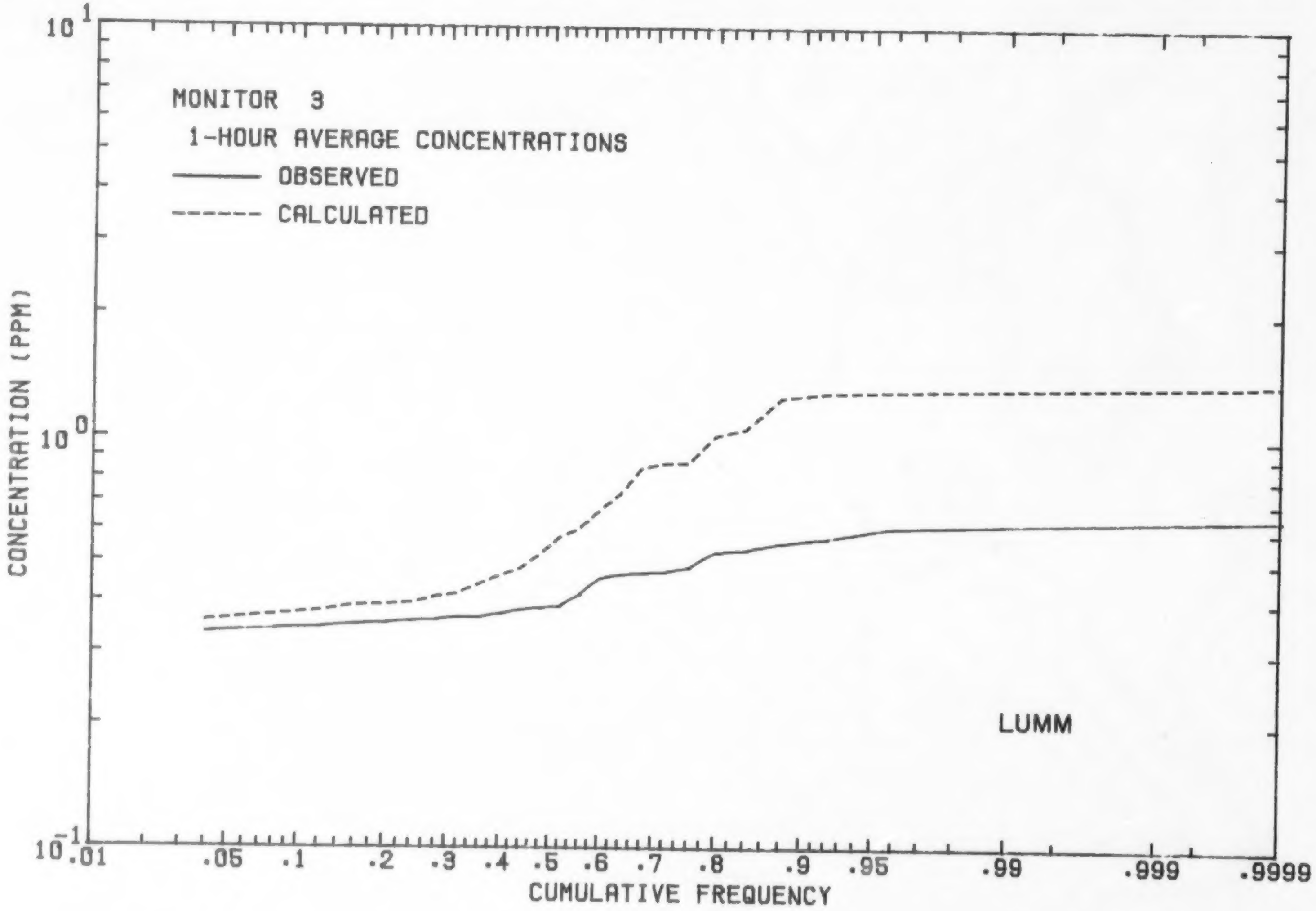

Figure E-4. Comparison of the cumulative frequency distribution of the 25 highest observed (minus background) 1-hour average SO_2 concentrations at Monitor 3 during the second year of the Westvaco monitoring program with the cumulative frequency distribution of the 25 highest 1-hour average concentrations calculated by LUMM.

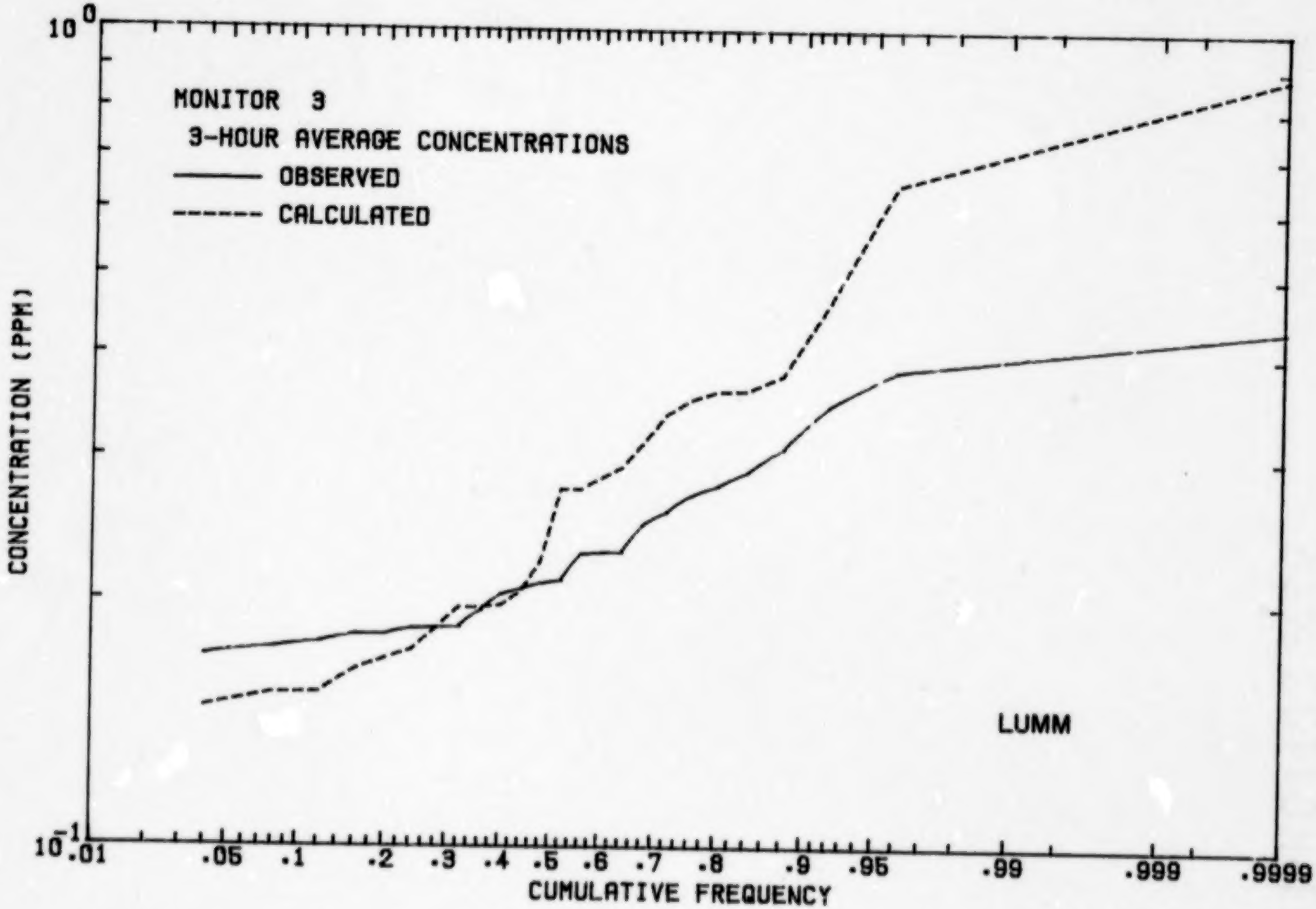

Figure E-5. Comparison of the cumulative frequency distribution of the 25 highest observed (minus background) 3-hour average SO_2 concentrations at Monitor 3 during the second year of the Westvaco monitoring program with the cumulative frequency distribution of the 25 highest 3-hour average concentrations calculated by LUMM.

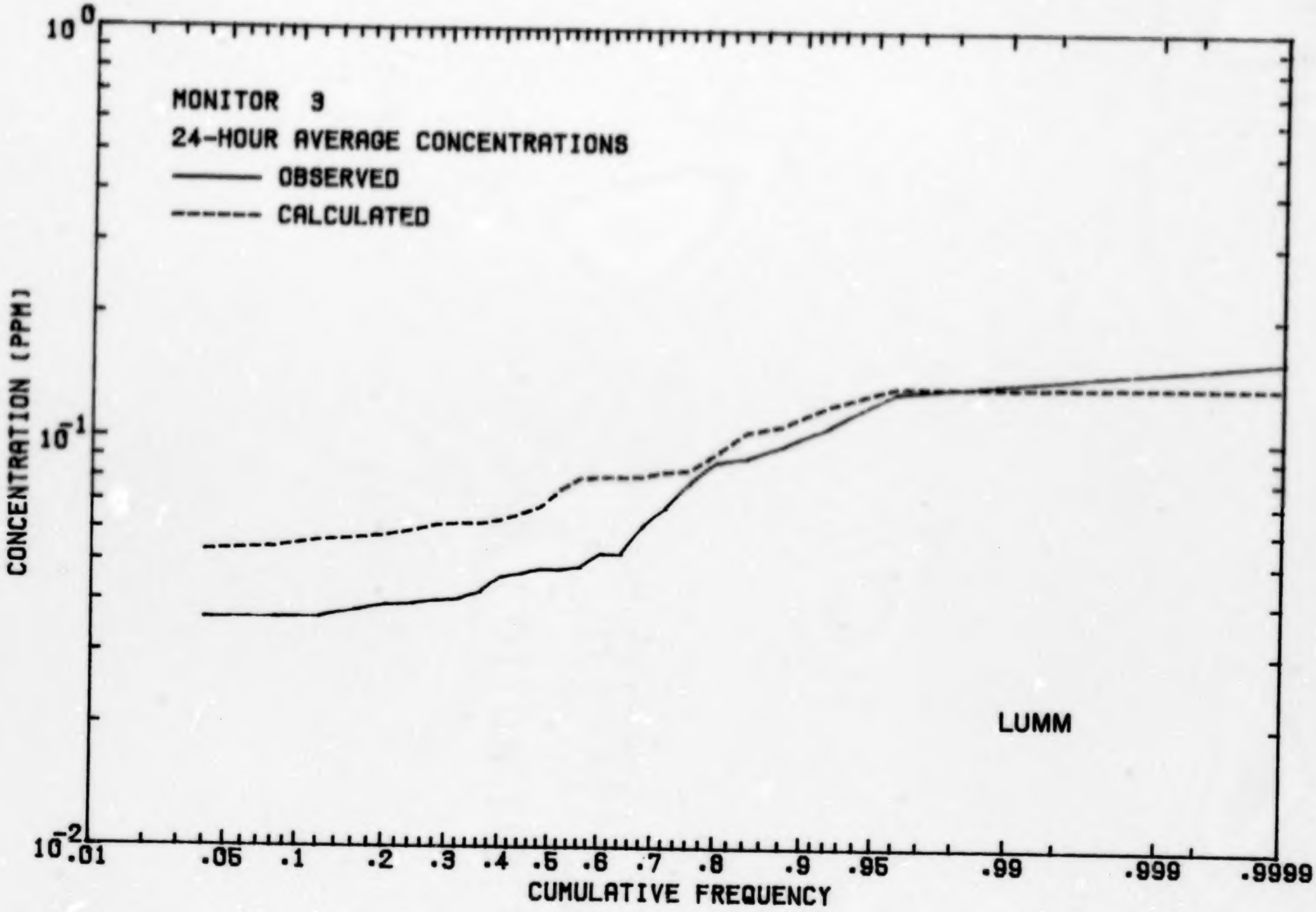

Figure E-6. Comparison of the cumulative frequency distribution of the 25 highest observed (minus background) 24-hour average SO_2 concentrations at Monitor 3 during the second year of the Westvaco monitoring program with the cumulative frequency distribution of the 25 highest 24-hour average concentrations calculated by LUMM.

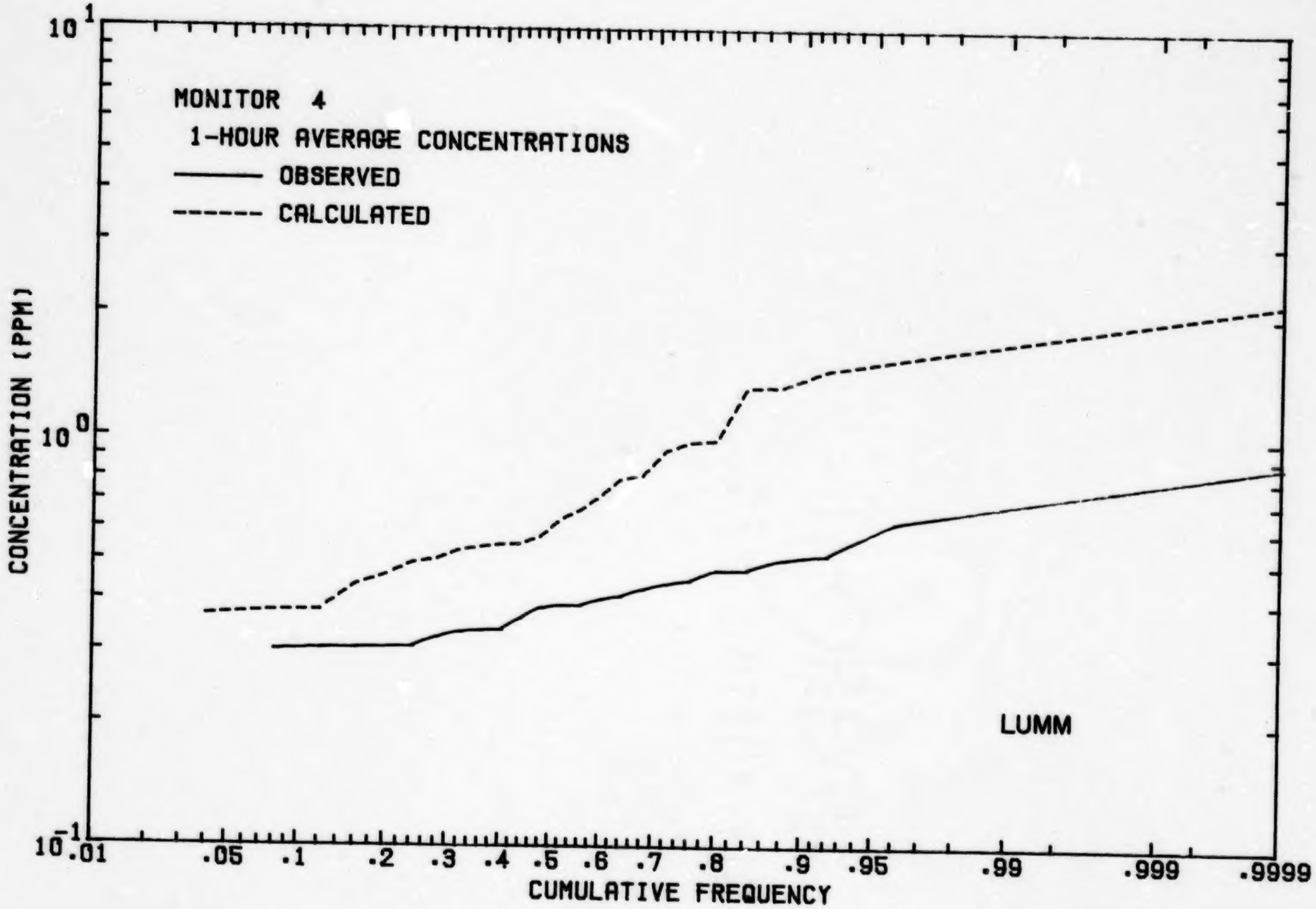

Figure E-7. Comparison of the cumulative frequency distribution of the 25 highest observed (minus background) 1-hour average SO_2 concentrations at Monitor 4 during the second year of the Westvaco monitoring program with the cumulative frequency distribution of the 25 highest 1-hour average concentrations calculated by LUMM.

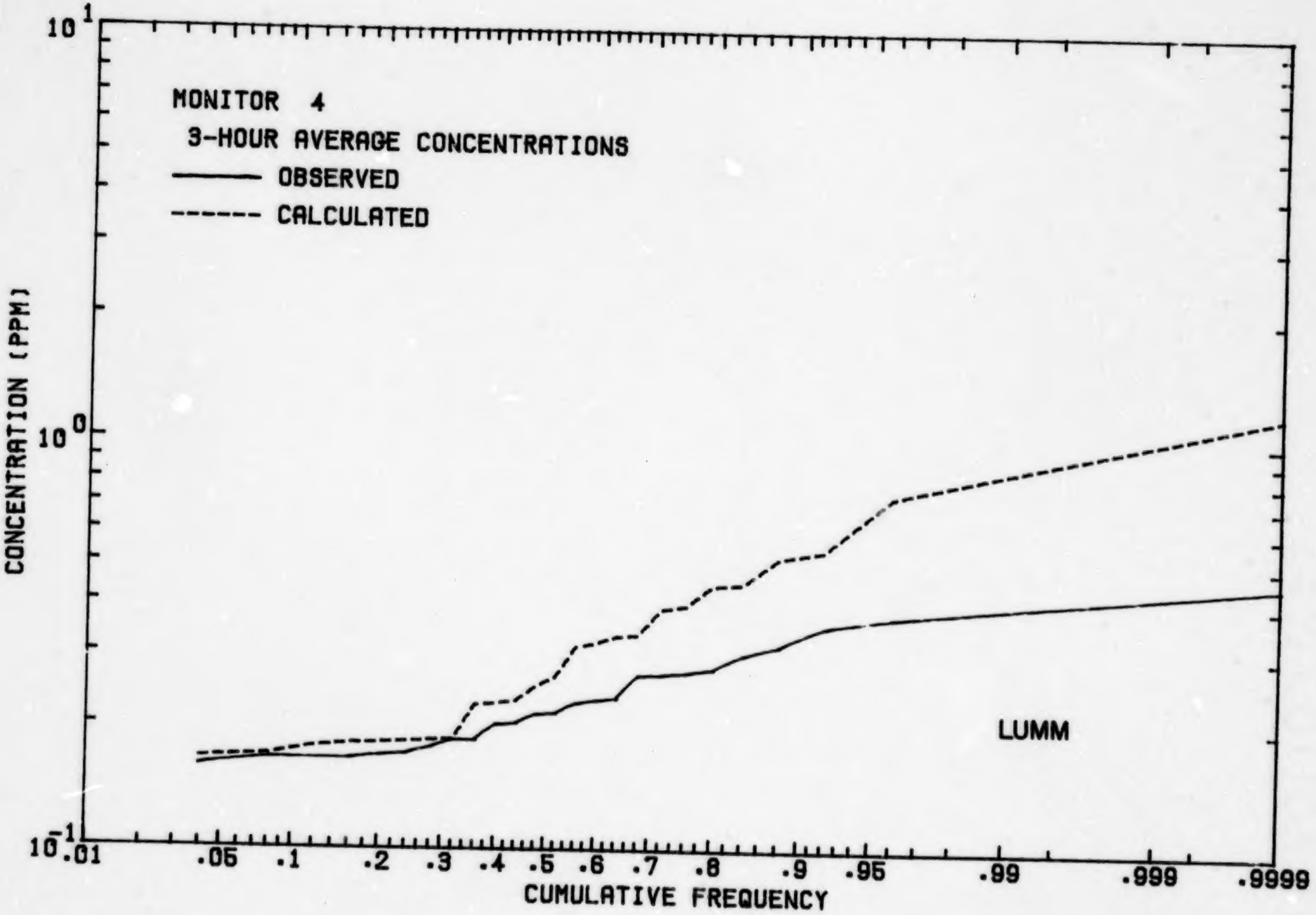

Figure E-8. Comparison of the cumulative frequency distribution of the 25 highest observed (minus background) 3-hour average SO_2 concentrations at Monitor 4 during the second year of the Westvaco monitoring program with the cumulative frequency distribution of the 25 highest 3-hour average concentrations calculated by LUMM.

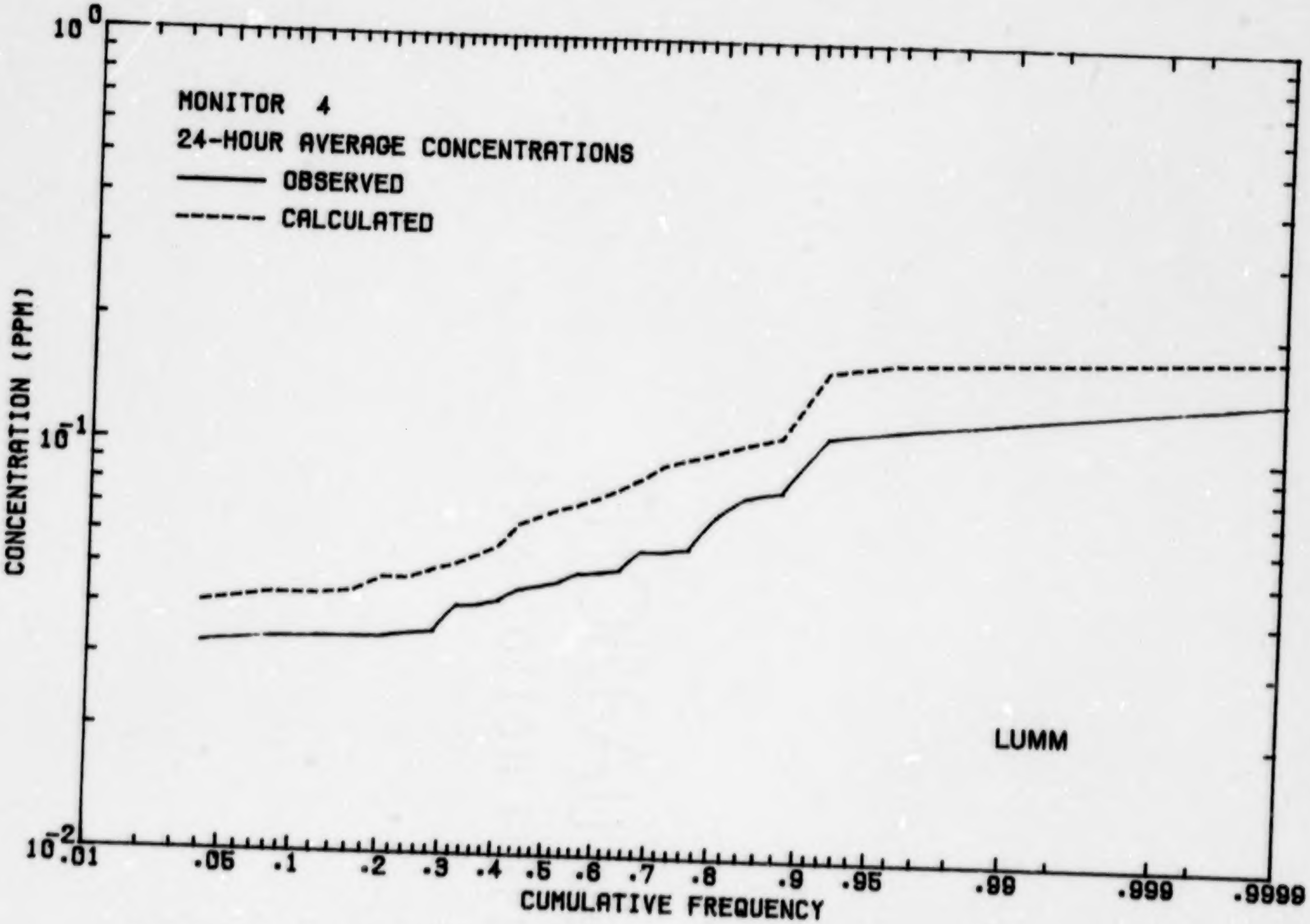

Figure E-9. Comparison of the cumulative frequency distribution of the 25 highest observed (minus background) 24-hour average SO_2 concentrations at Monitor 4 during the second year of the Westvaco monitoring program with the cumulative frequency distribution of the 25 highest 24-hour average concentrations calculated by LUMM.

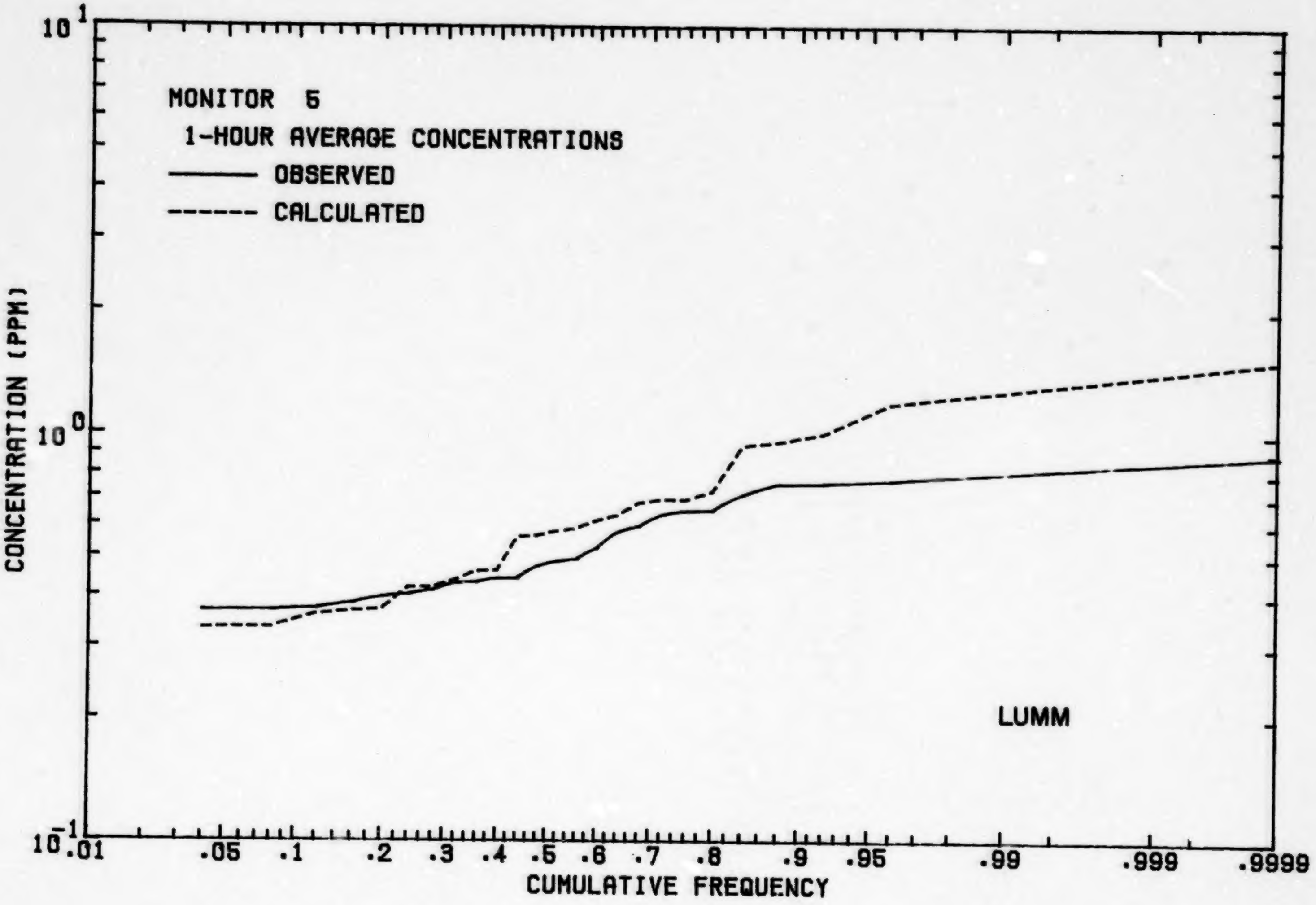

Figure E-10. Comparison of the cumulative frequency distribution of the 25 highest observed (minus background) 1-hour average SO_2 concentrations at Monitor 5 during the second year of the Westvaco monitoring program with the cumulative frequency distribution of the 25 highest 1-hour average concentrations calculated by LUMM.

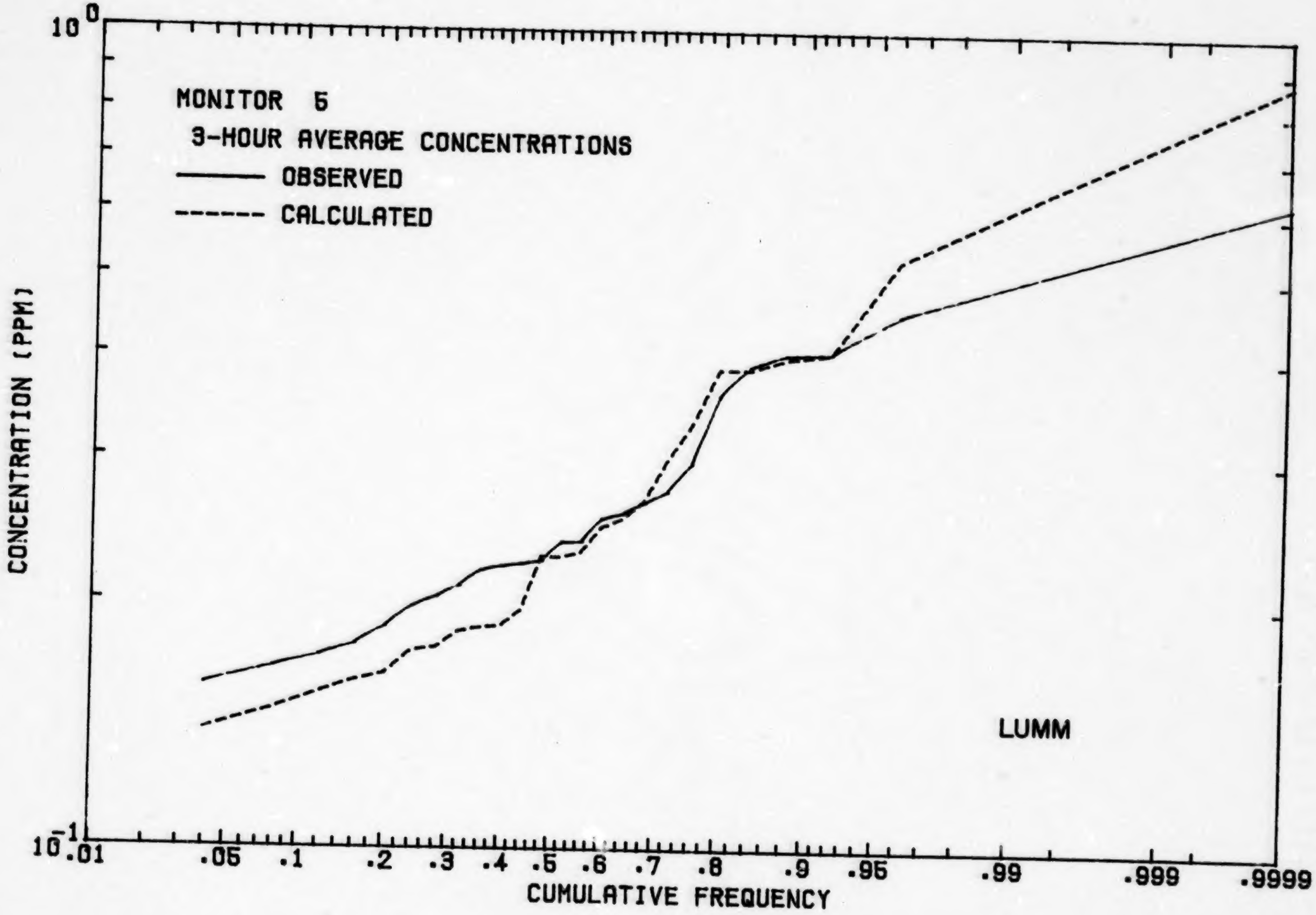

Figure E-11. Comparison of the cumulative frequency distribution of the 25 highest observed (minus background) 3-hour average SO_2 concentrations at Monitor 5 during the second year of the Westvaco monitoring program with the cumulative frequency distribution of the 25 highest 3-hour average concentrations calculated by LUMM.

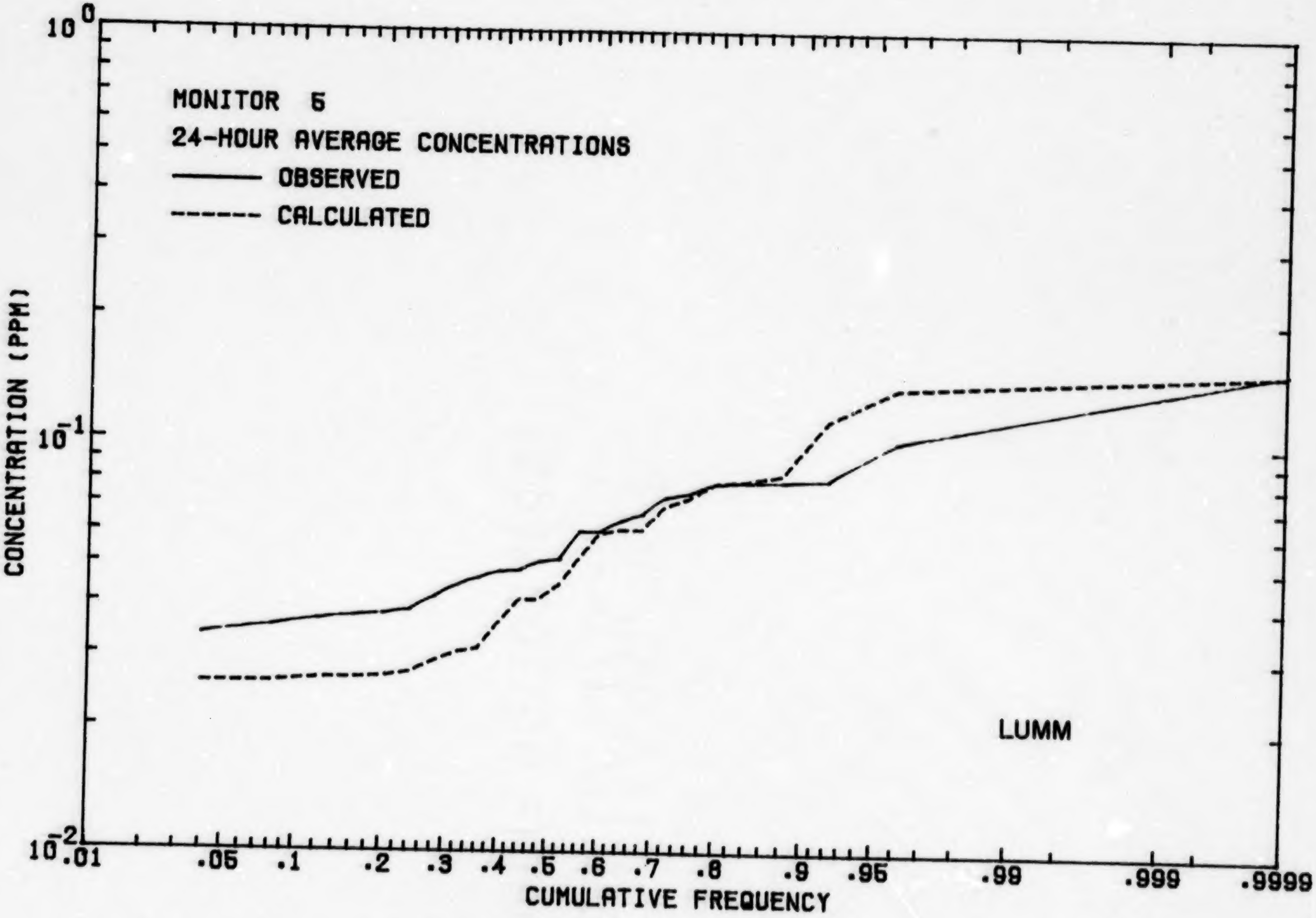

Figure E-12. Comparison of the cumulative frequency distribution of the 25 highest observed (minus background) 24-hour average SO_2 concentrations at Monitor 5 during the second year of the Westvaco monitoring program with the cumulative frequency distribution of the 25 highest 24-hour average concentrations calculated by LUMM.

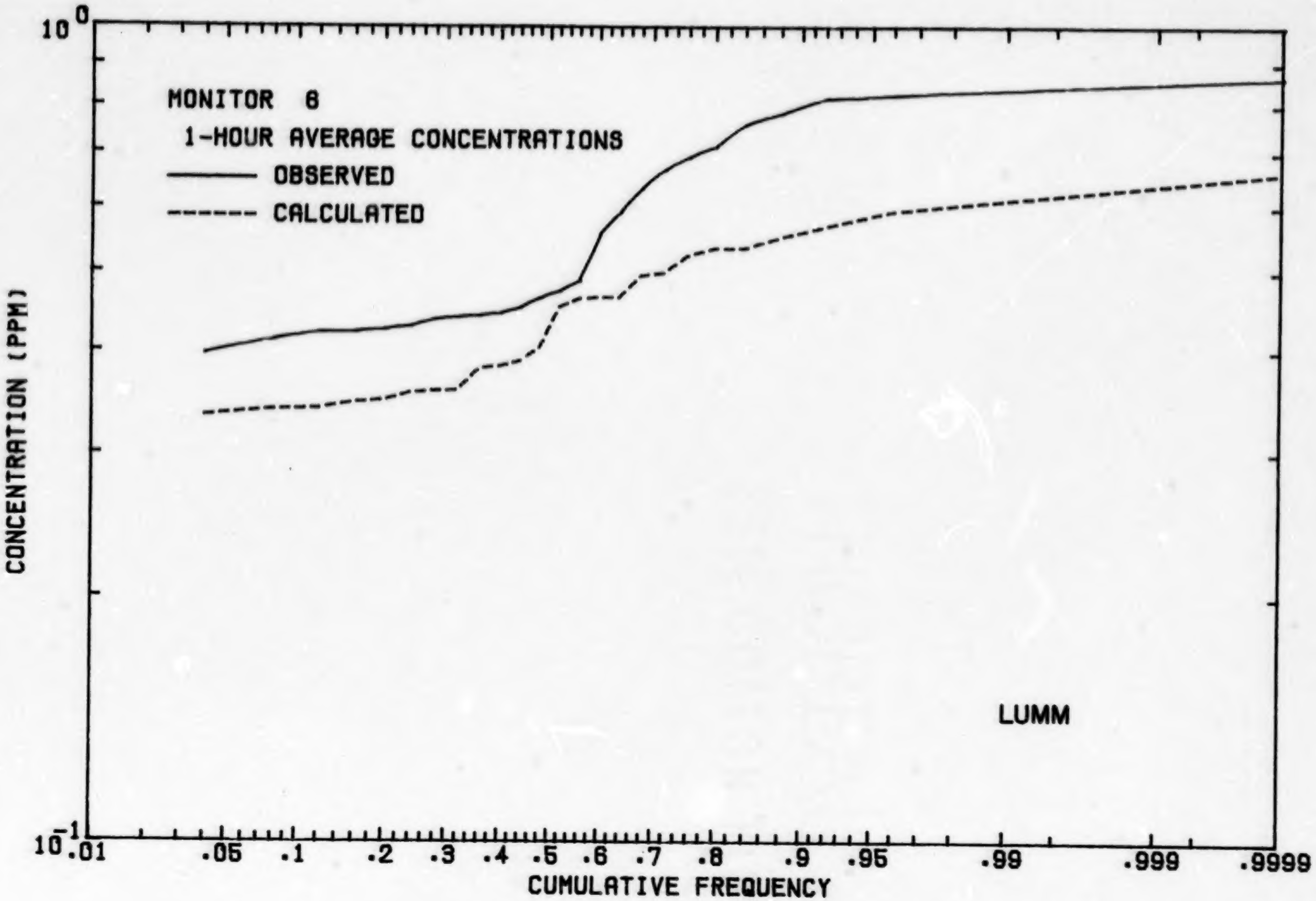

Figure E-13. Comparison of the cumulative frequency distribution of the 25 highest observed (minus background) 1-hour average SO_2 concentrations at Monitor 6 during the second year of the Westvaco monitoring program with the cumulative frequency distribution of the 25 highest 1-hour average concentrations calculated by LUMM.

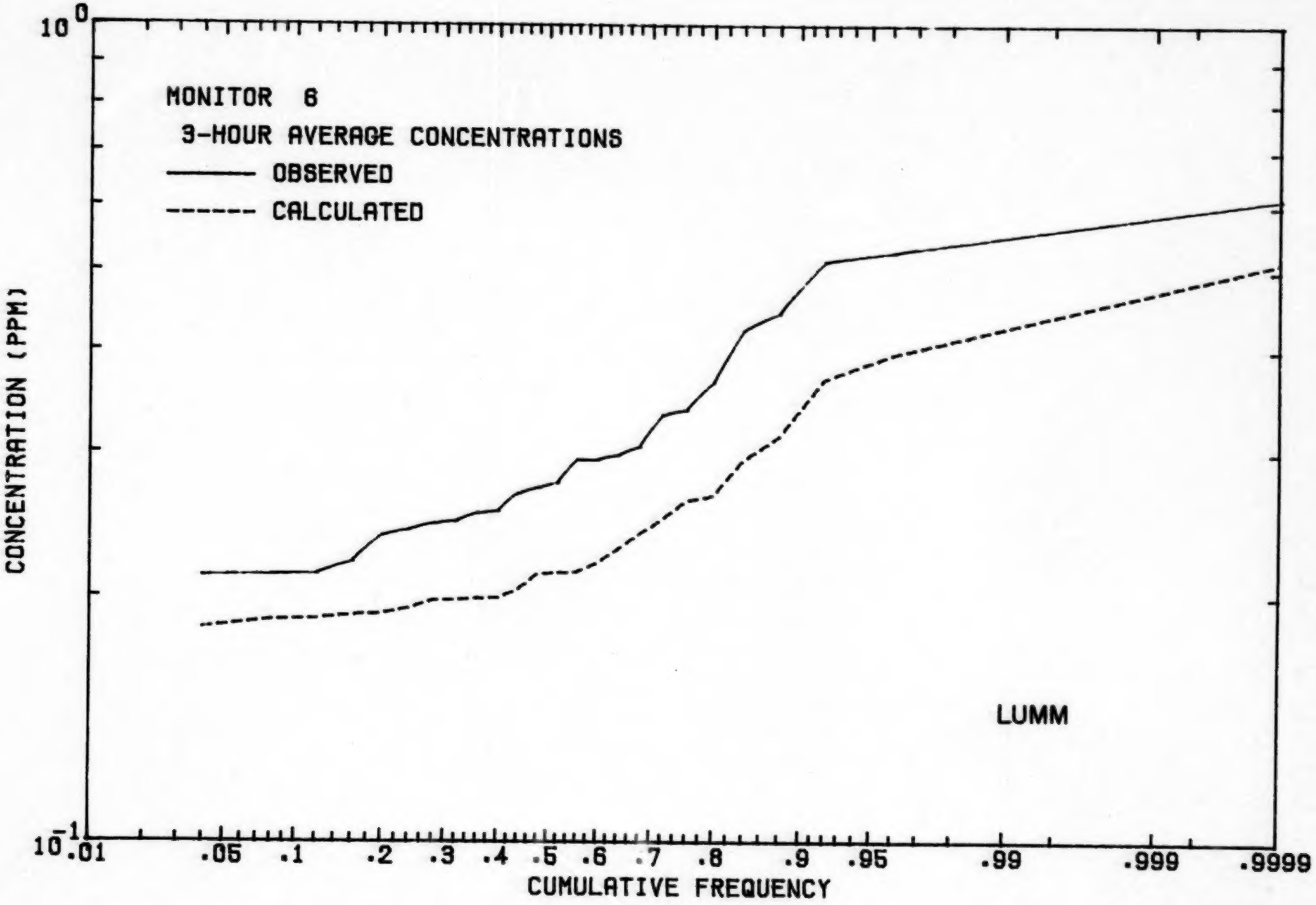

Figure E-14. Comparison of the cumulative frequency distribution of the 25 highest observed (minus background) 3-hour average SO_2 concentrations at Monitor 6 during the second year of the Westvaco monitoring program with the cumulative frequency distribution of the 25 highest 3-hour average concentrations calculated by LUMM.

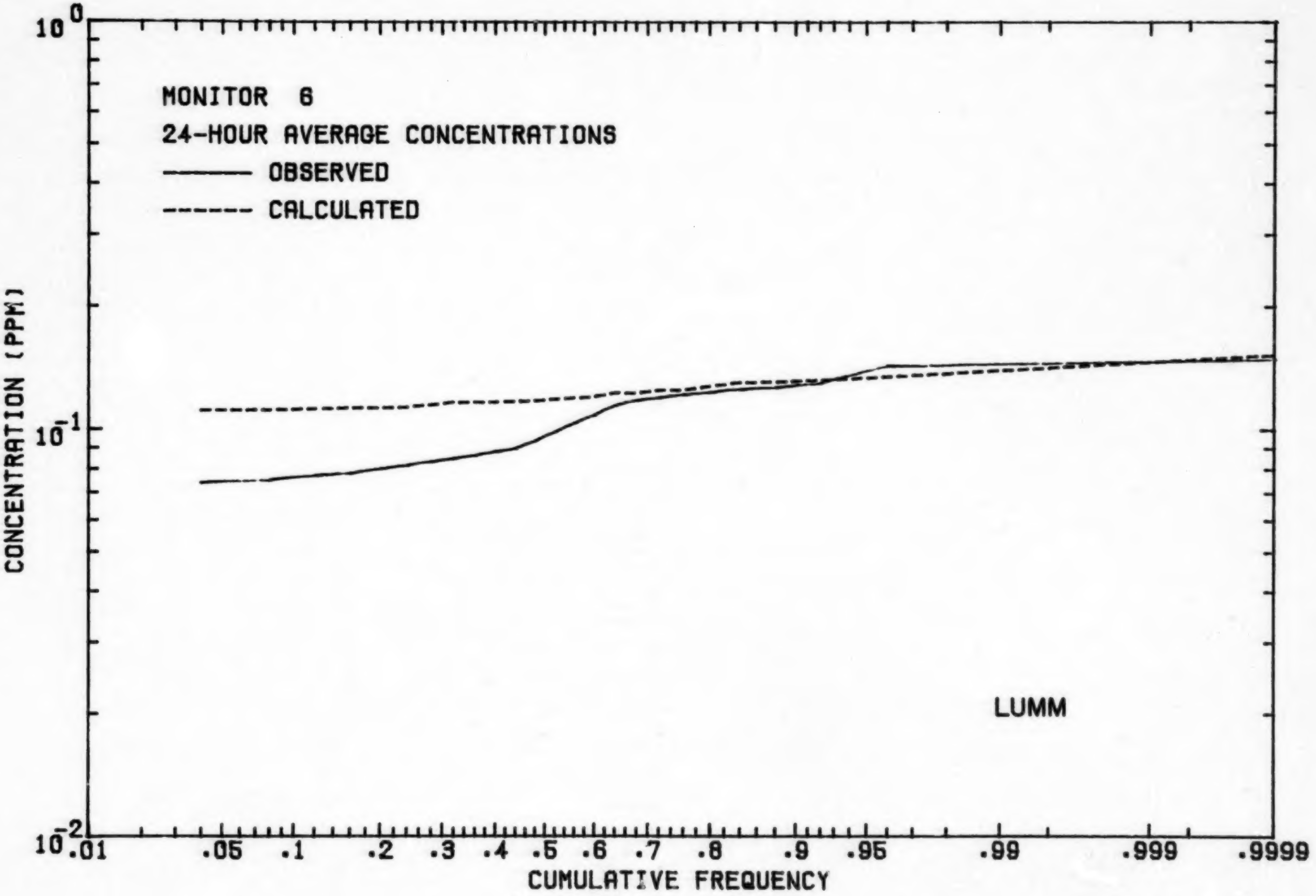

Figure E-15. Comparison of the cumulative frequency distribution of the 25 highest observed (minus background) 24-hour average SO_2 concentrations at Monitor 6 during the second year of the Westvaco monitoring program with the cumulative frequency distribution of the 25 highest 24-hour average concentrations calculated by LUMM.

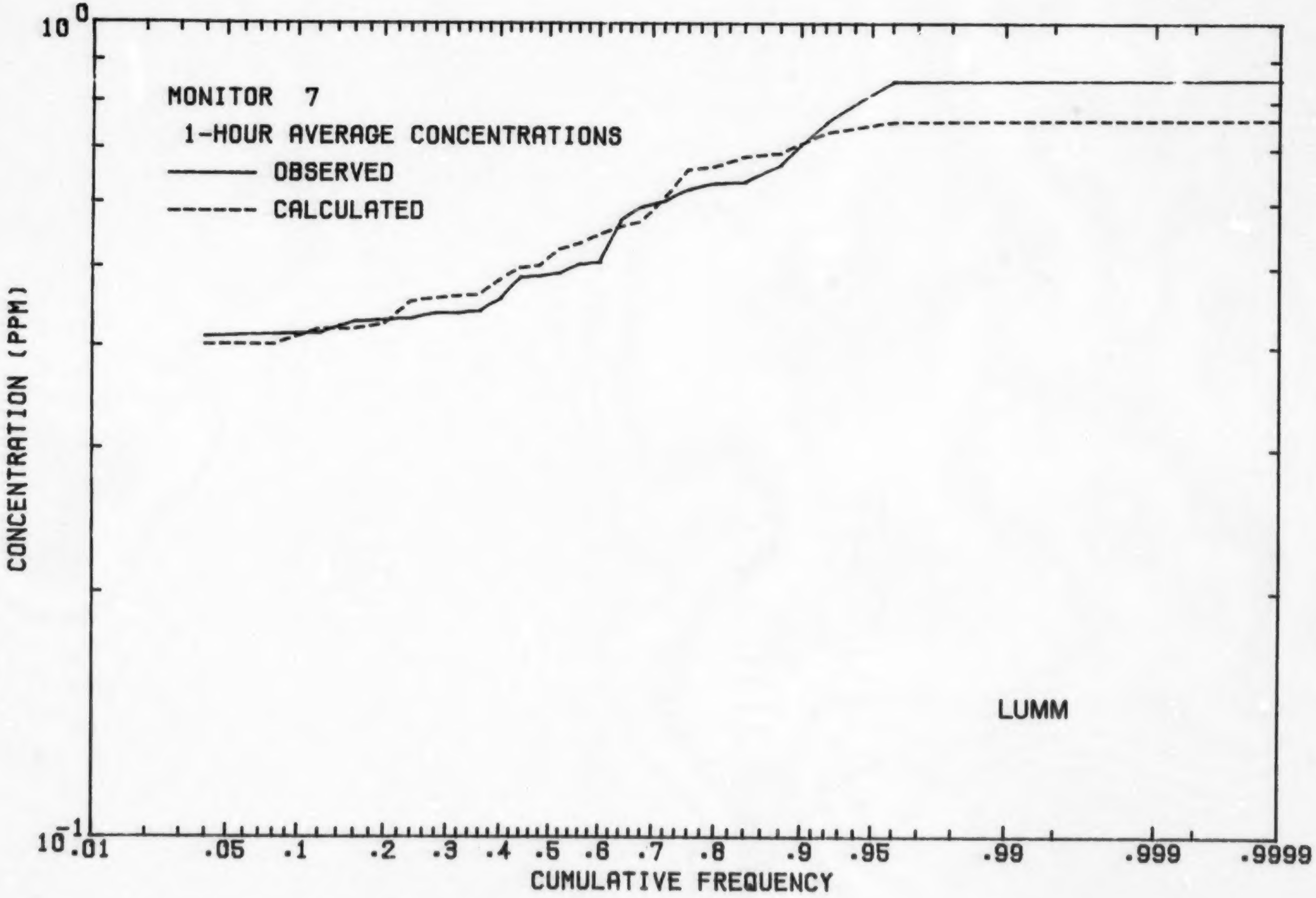

Figure E-16. Comparison of the cumulative frequency distribution of the 25 highest observed (minus background) 1-hour average SO_2 concentrations at Monitor 7 during the second year of the Westvaco monitoring program with the cumulative frequency distribution of the 25 highest 1-hour average concentrations calculated by LUMM.

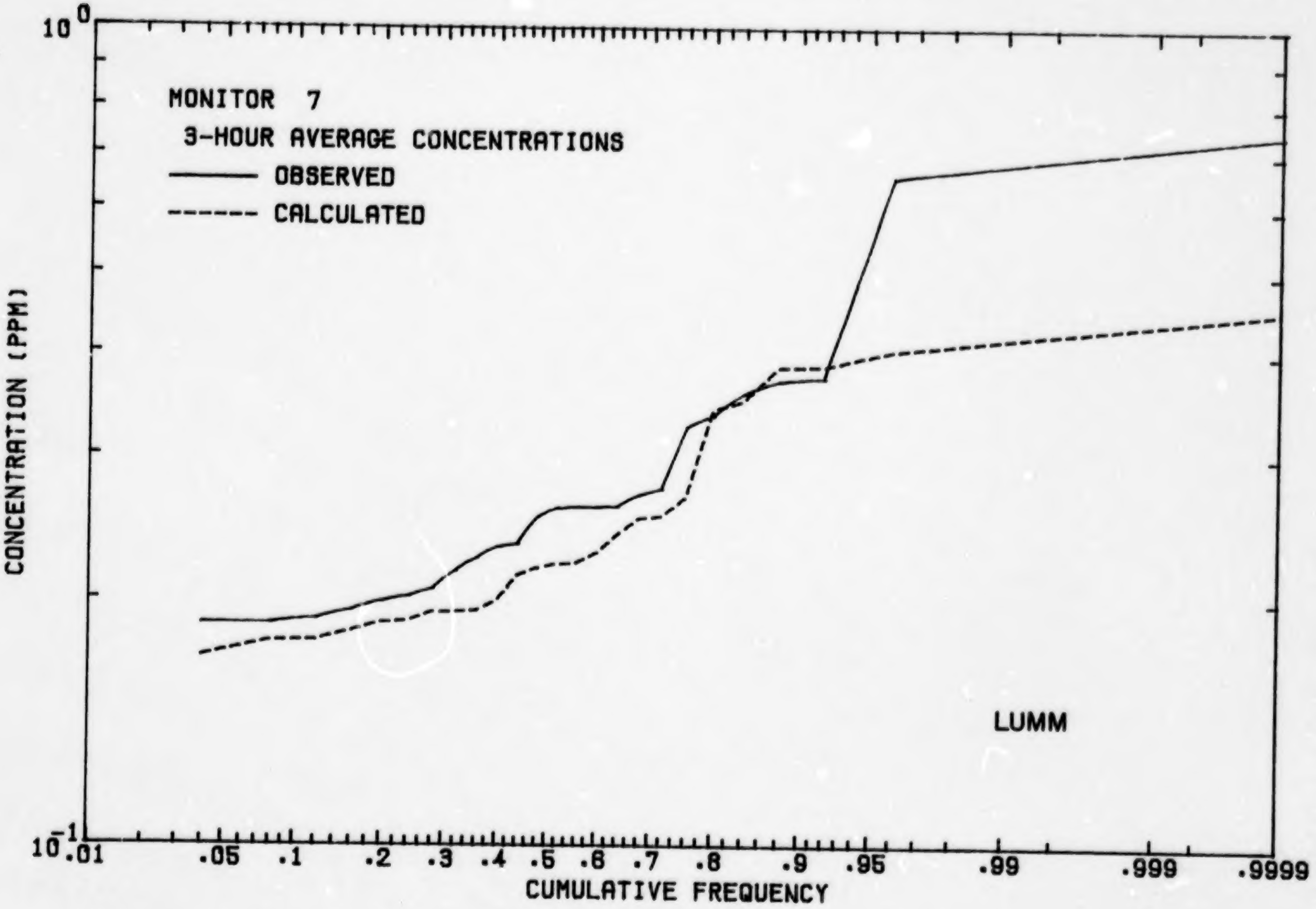

Figure E-17. Comparison of the cumulative frequency distribution of the 25 highest observed (minus background) 3-hour average SO_2 concentrations at Monitor 7 during the second year of the Westvaco monitoring program with the cumulative frequency distribution of the 25 highest 3-hour average concentrations calculated by LUMM.

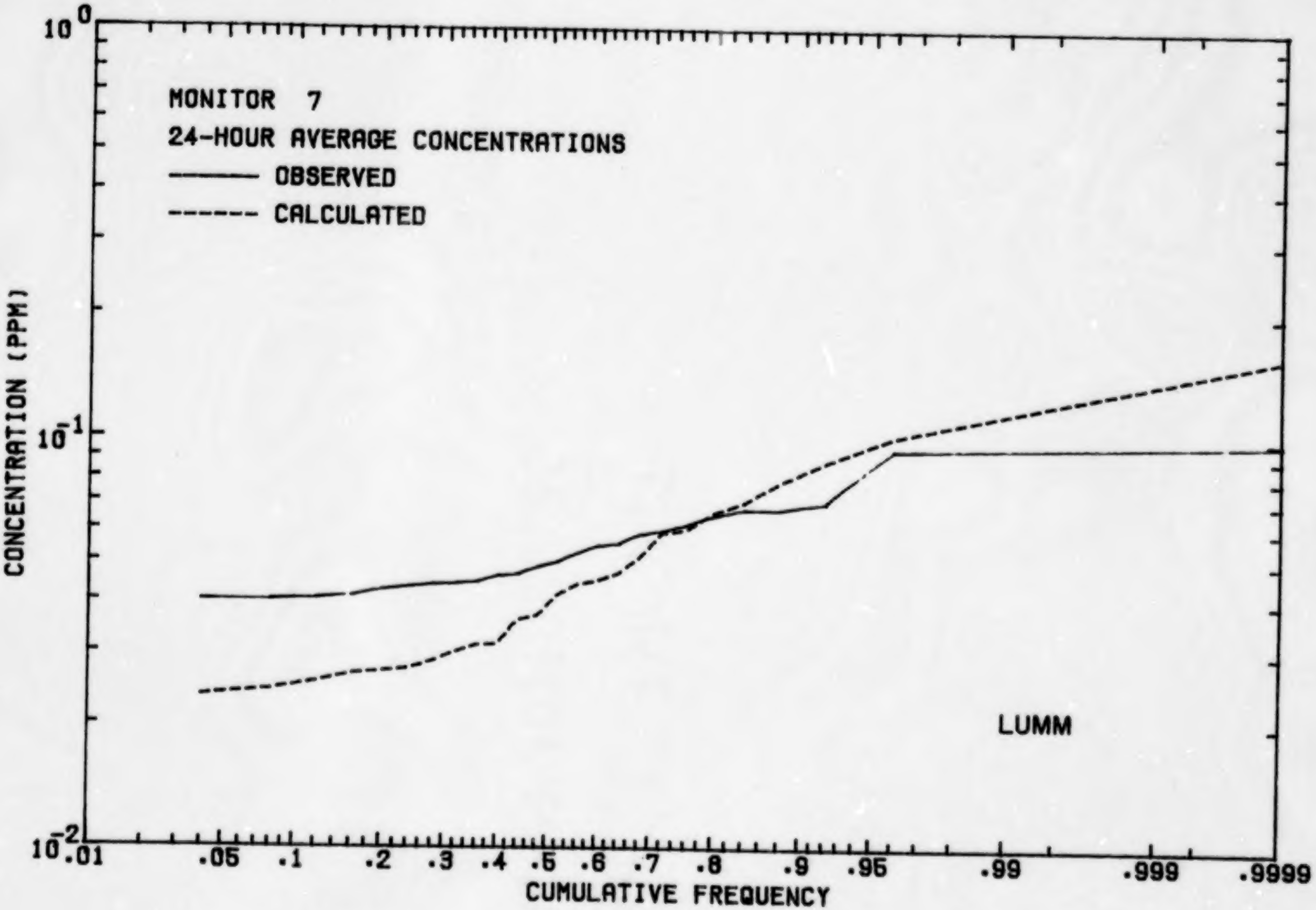

Figure E-18. Comparison of the cumulative frequency distribution of the 25 highest observed (minus background) 24-hour average SO_2 concentrations at Monitor 7 during the second year of the Westvaco monitoring program with the cumulative frequency distribution of the 25 highest 24-hour average concentrations calculated by LUMM.

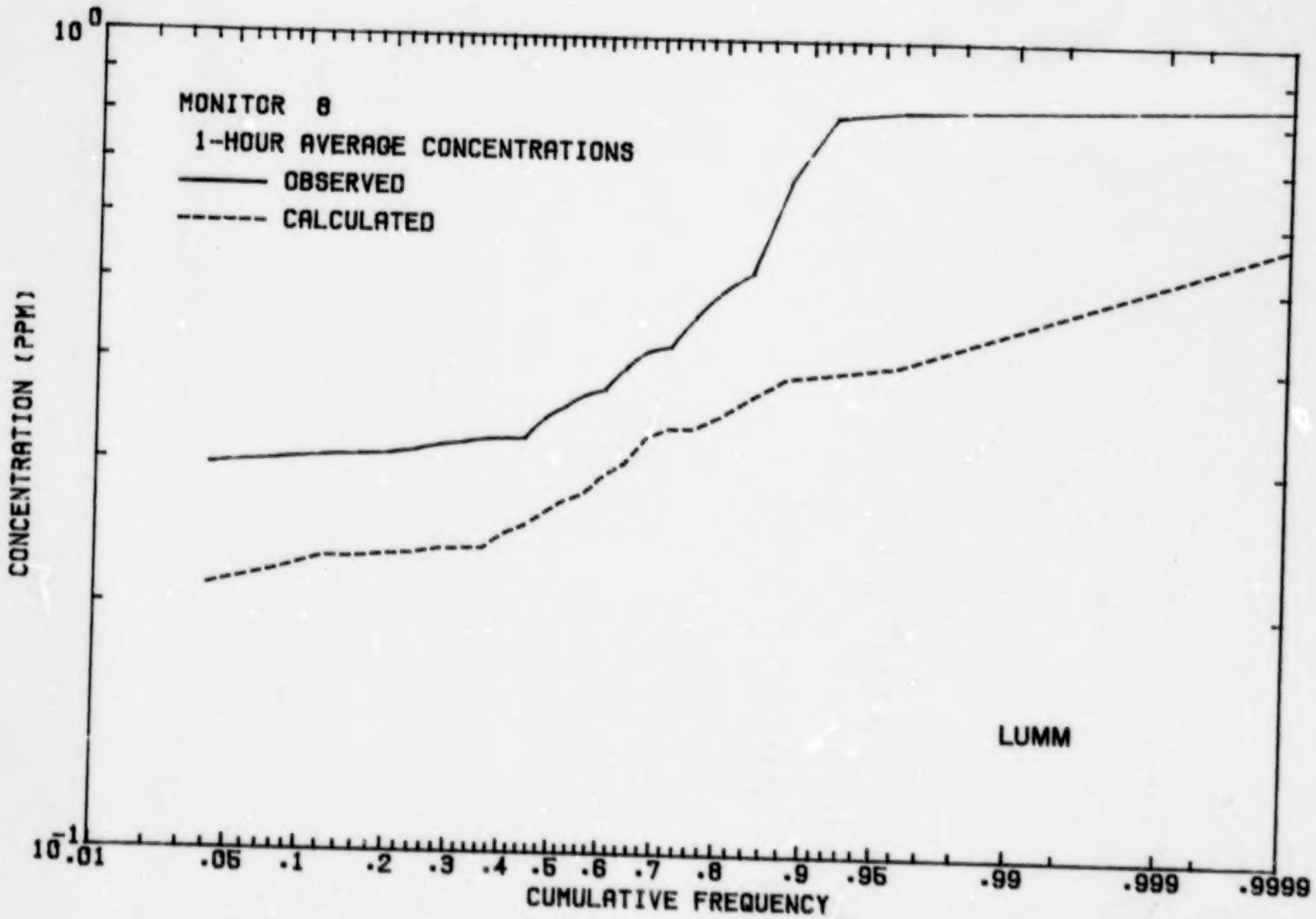

Figure E-19. Comparison of the cumulative frequency distribution of the 25 highest observed (minus background) 1-hour average SO_2 concentrations at Monitor 8 during the second year of the Westvaco monitoring program with the cumulative frequency distribution of the 25 highest 1-hour average concentrations calculated by LUMM.

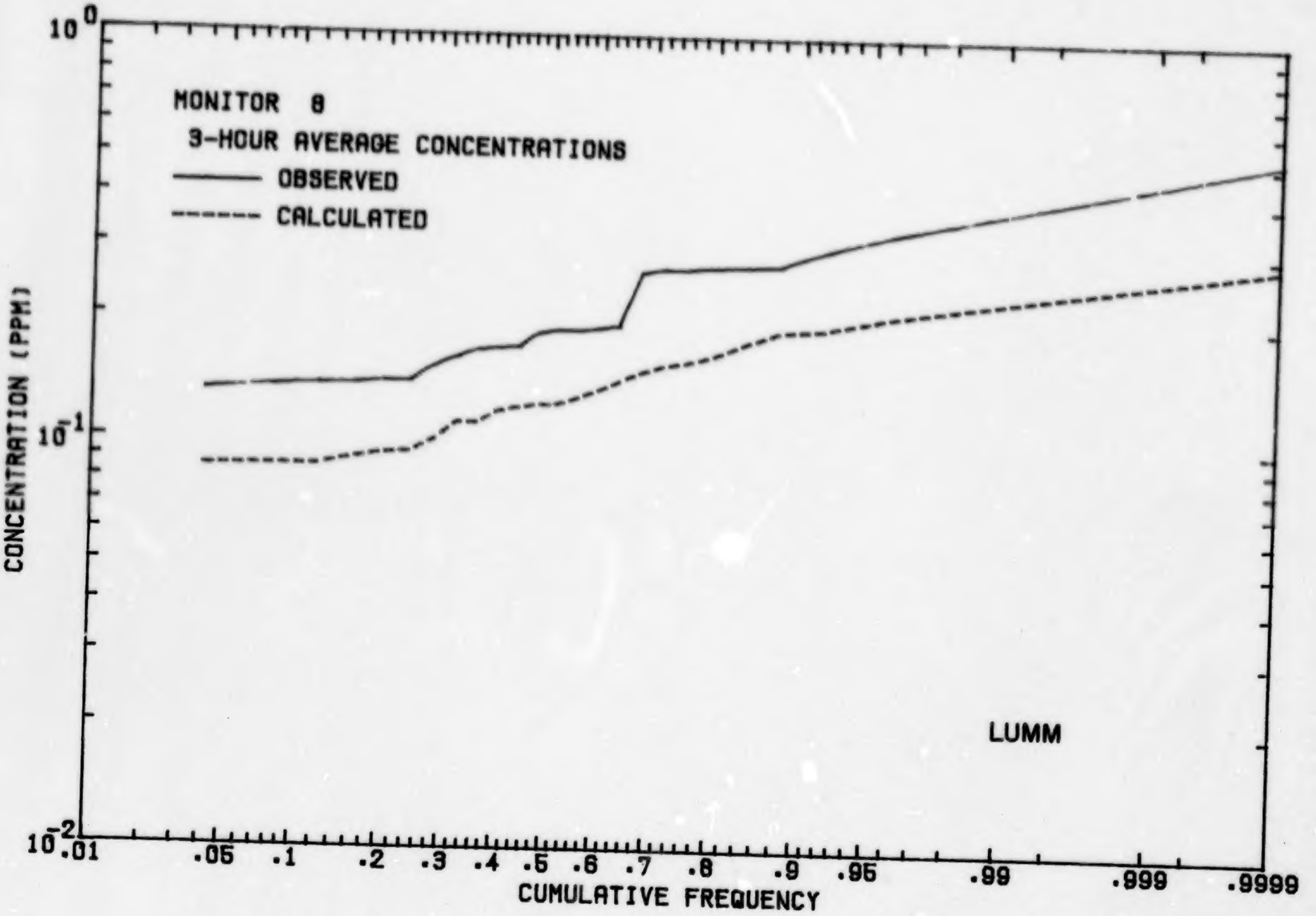

Figure E-20. Comparison of the cumulative frequency distribution of the 25 highest observed (minus background) 3-hour average SO_2 concentrations at Monitor 8 during the second year of the Westvaco monitoring program with the cumulative frequency distribution of the 25 highest 3-hour average concentrations calculated by LUMM.

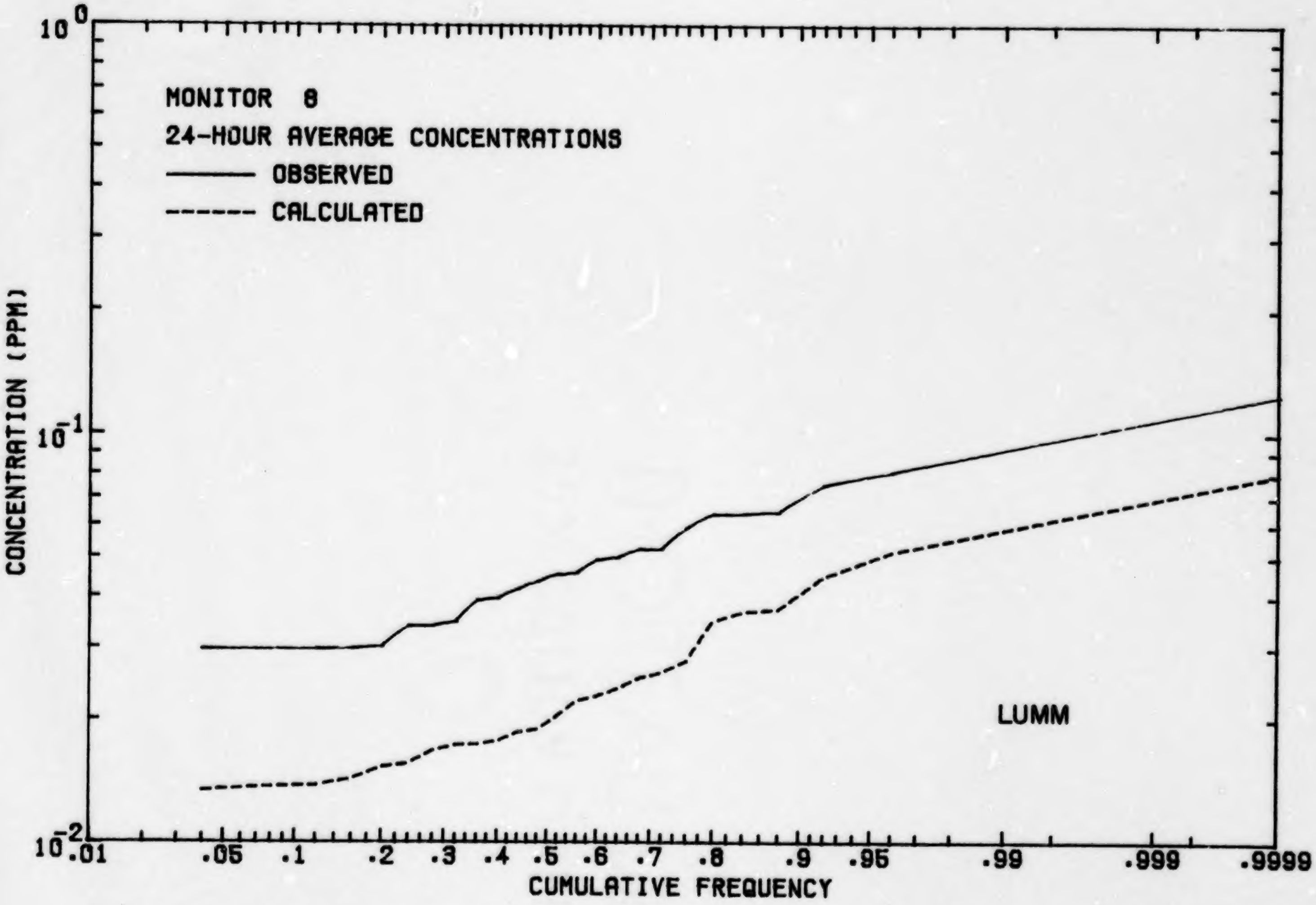

Figure E-21. Comparison of the cumulative frequency distribution of the 25 highest observed (minus background) 24-hour average SO_2 concentrations at Monitor 8 during the second year of the Westvaco monitoring program with the cumulative frequency distribution of the 25 highest 24-hour average concentrations calculated by LUMM.

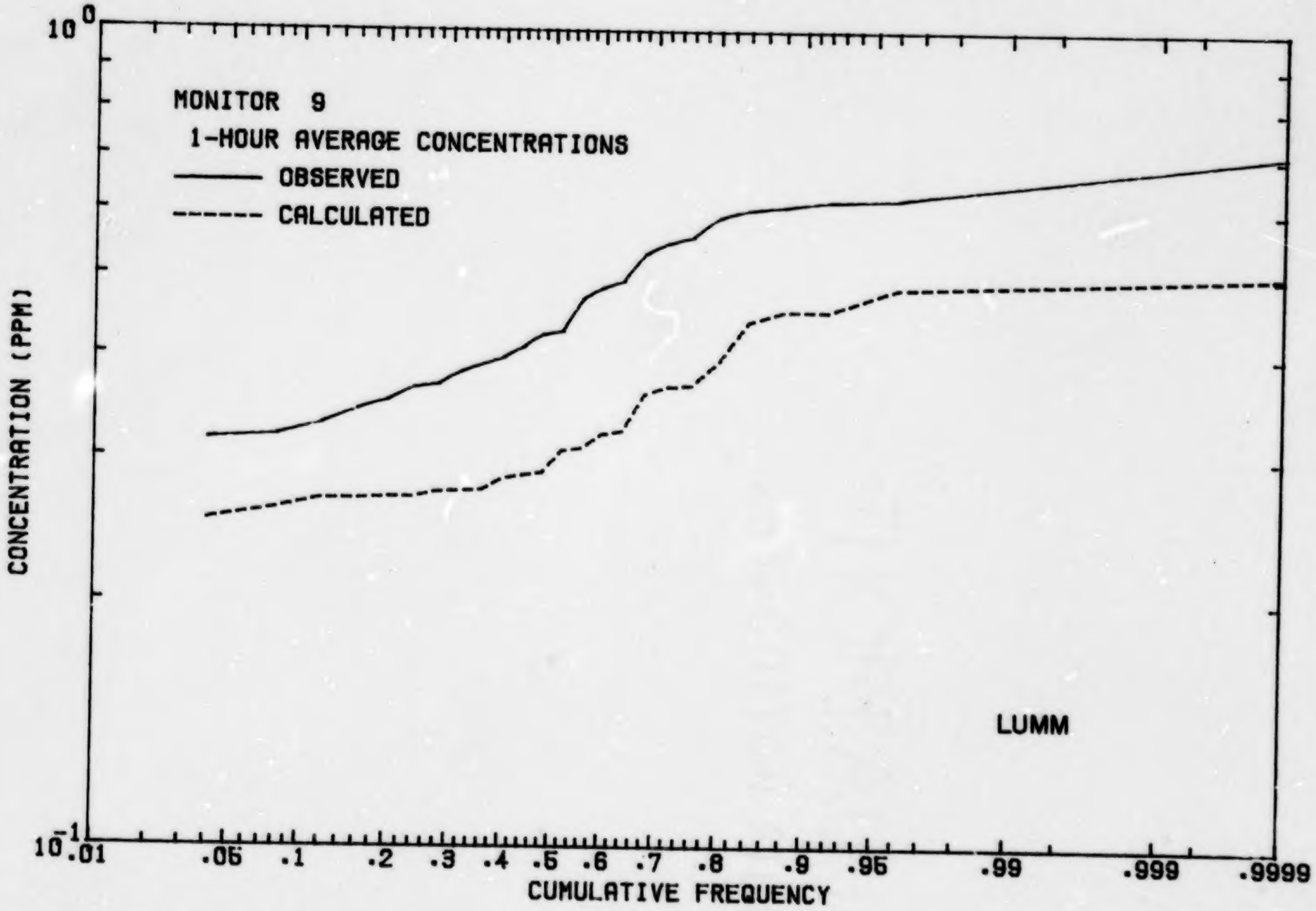

Figure E-22. Comparison of the cumulative frequency distribution of the 25 highest observed (minus background) 1-hour average SO_2 concentrations at Monitor 9 during the second year of the Westvaco monitoring program with the cumulative frequency distribution of the 25 highest 1-hour average concentrations calculated by LUMM.

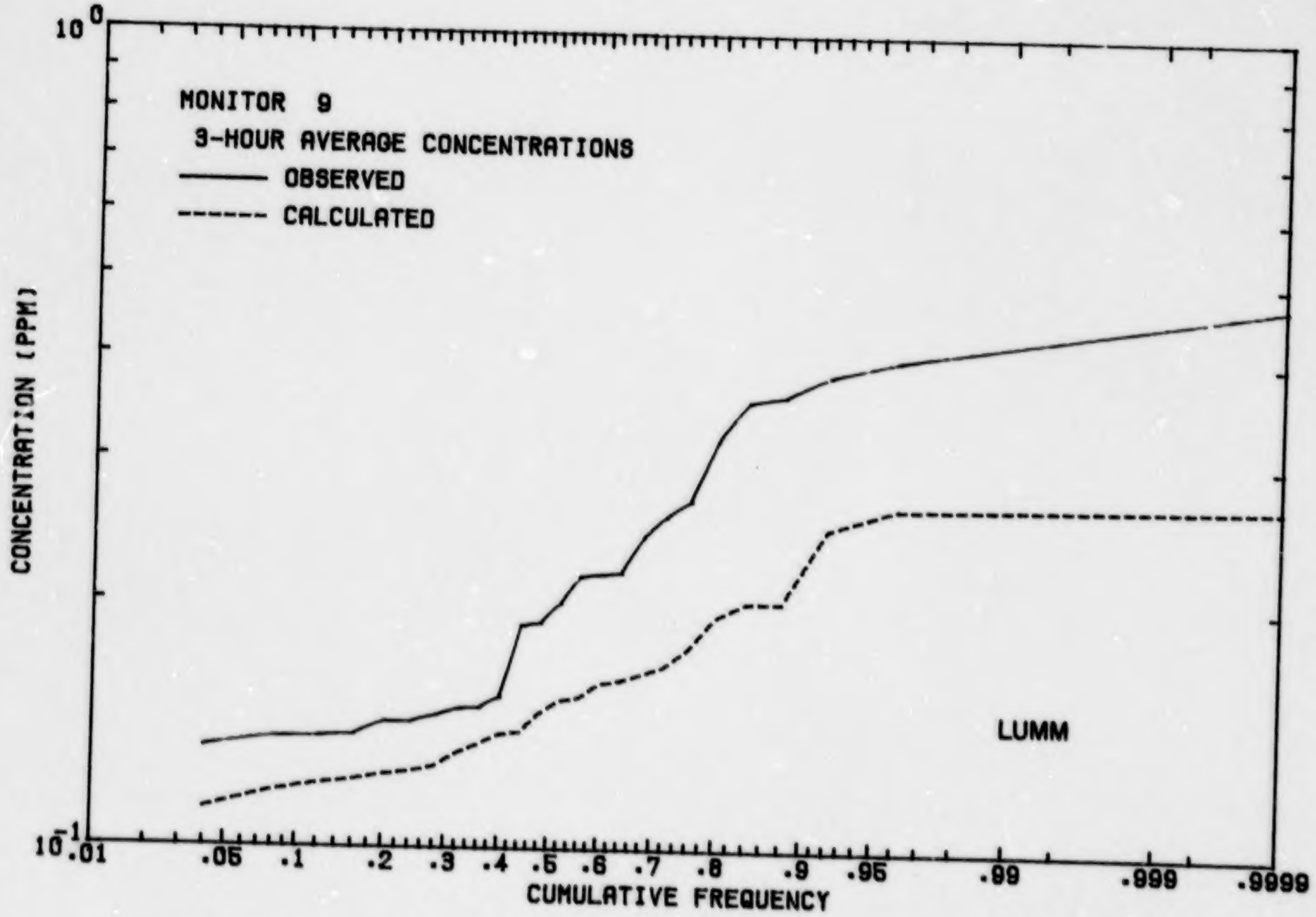

Figure E-23. Comparison of the cumulative frequency distribution of the 25 highest observed (minus background) 3-hour average SO_2 concentrations at Monitor 9 during the second year of the Westvaco monitoring program with the cumulative frequency distribution of the 25 highest 3-hour average concentrations calculated by LUMM.

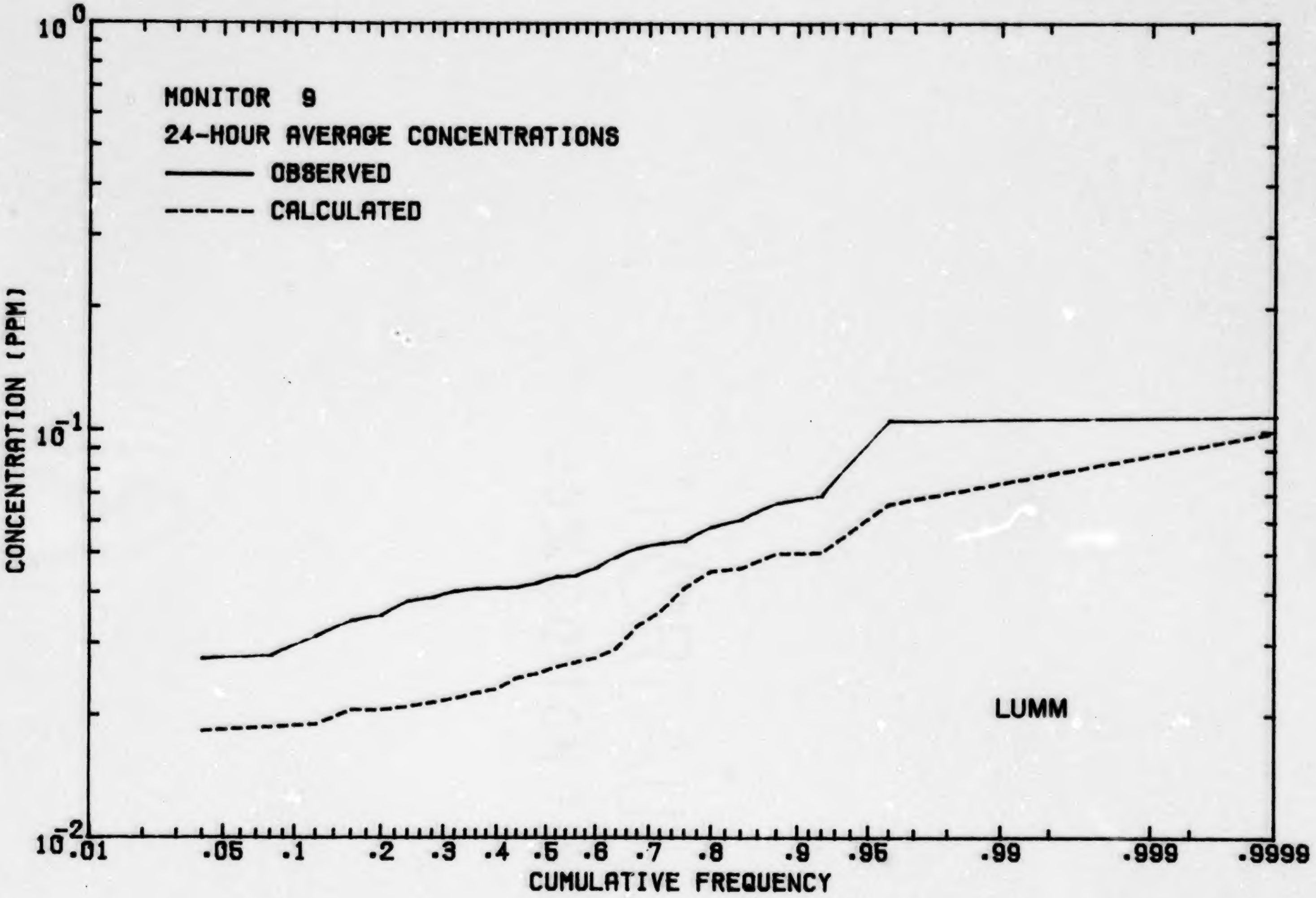

Figure E-24. Comparison of the cumulative frequency distribution of the 25 highest observed (minus background) 24-hour average SO_2 concentrations at Monitor 9 during the second year of the Westvaco monitoring program with the cumulative frequency distribution of the 25 highest 24-hour average concentrations calculated by LUMM.

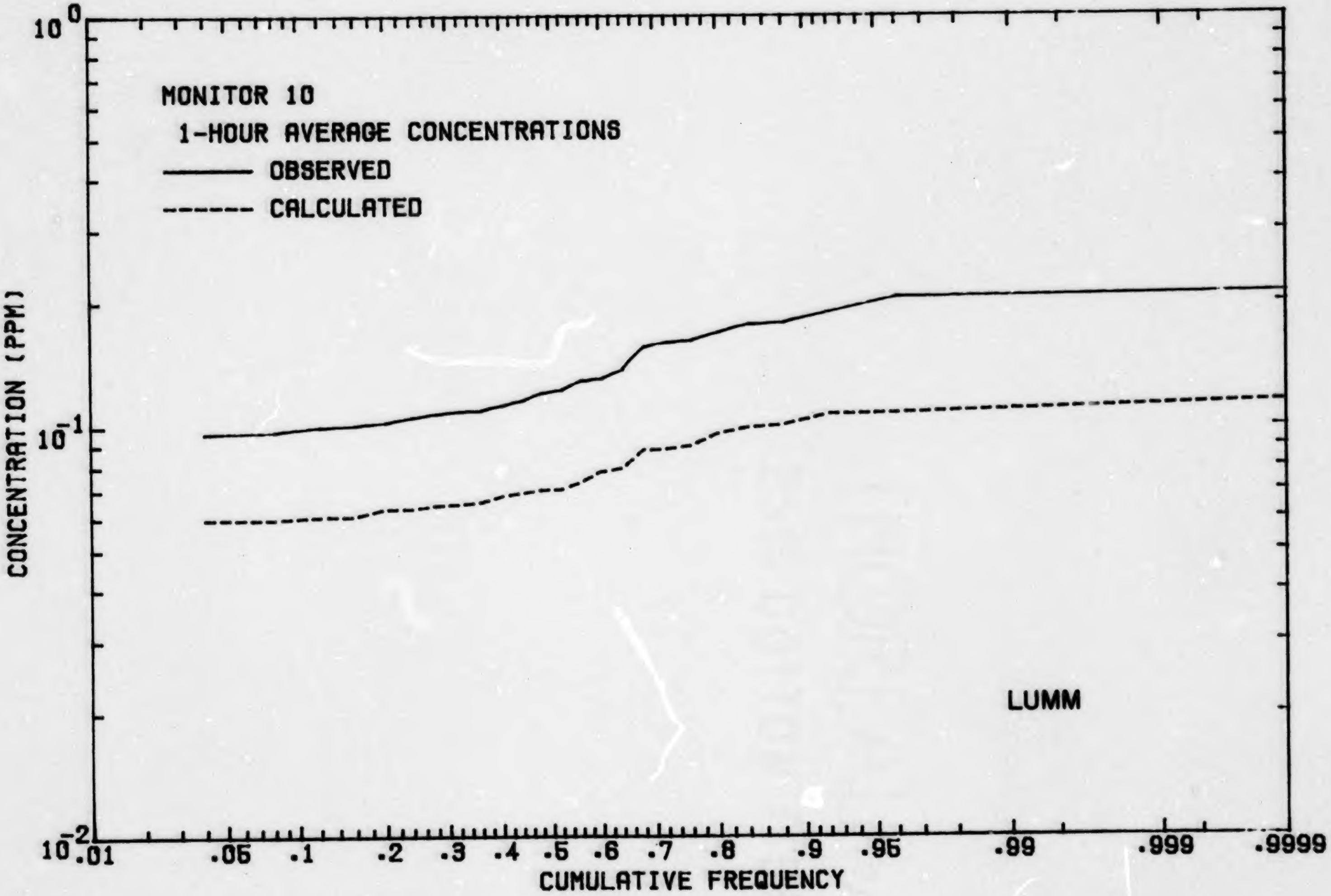

Figure E-25. Comparison of the cumulative frequency distribution of the 25 highest observed (minus background) 1-hour average SO_2 concentrations at Monitor 10 during the second year of the Westvaco monitoring program with the cumulative frequency distribution of the 25 highest 1-hour average concentrations calculated by LUMM.

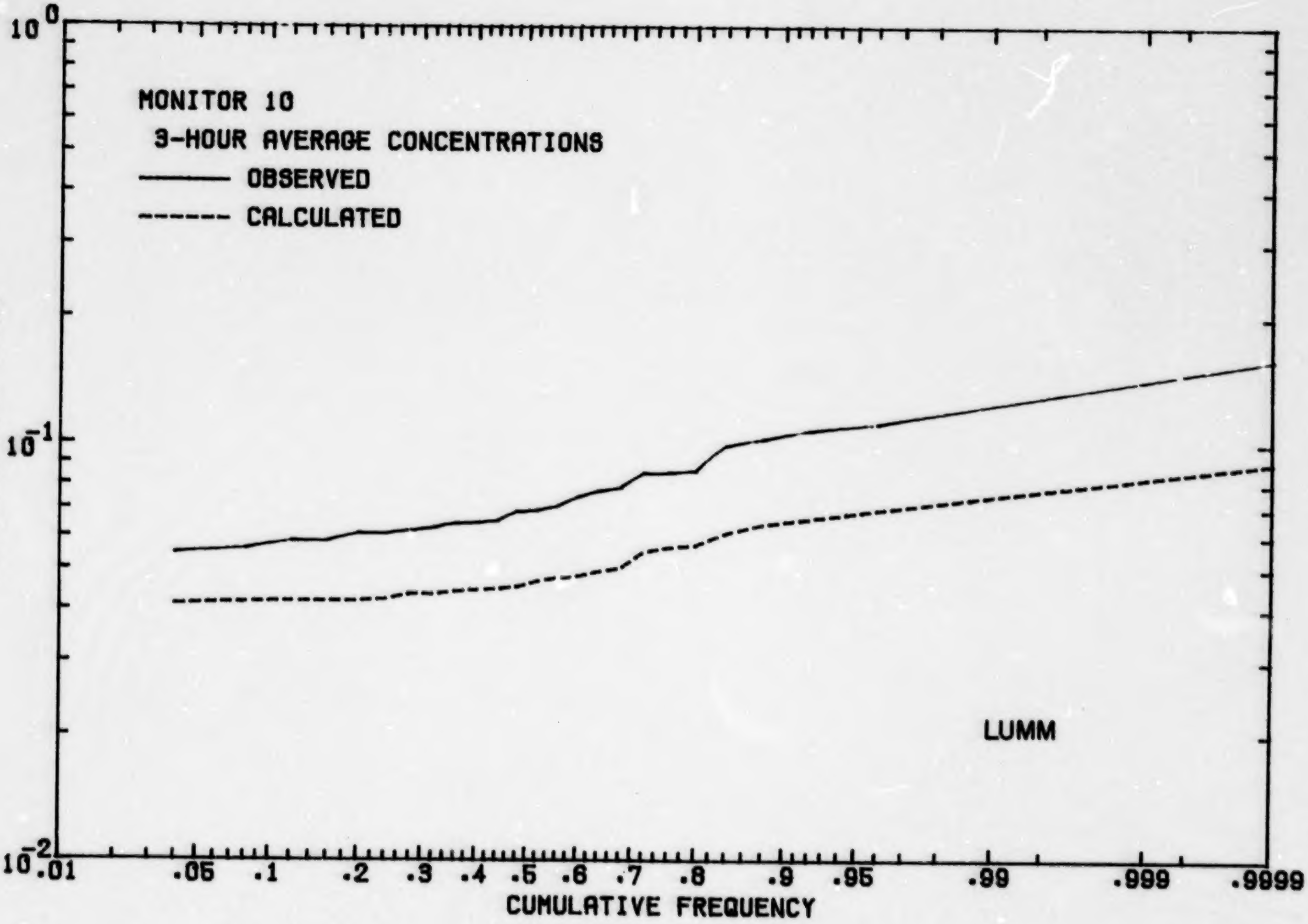

Figure E-26. Comparison of the cumulative frequency distribution of the 25 highest observed (minus background) 3-hour average SO_2 concentrations at Monitor 10 during the second year of the Westvaco monitoring program with the cumulative frequency distribution of the 25 highest 3-hour average concentrations calculated by LUMM.

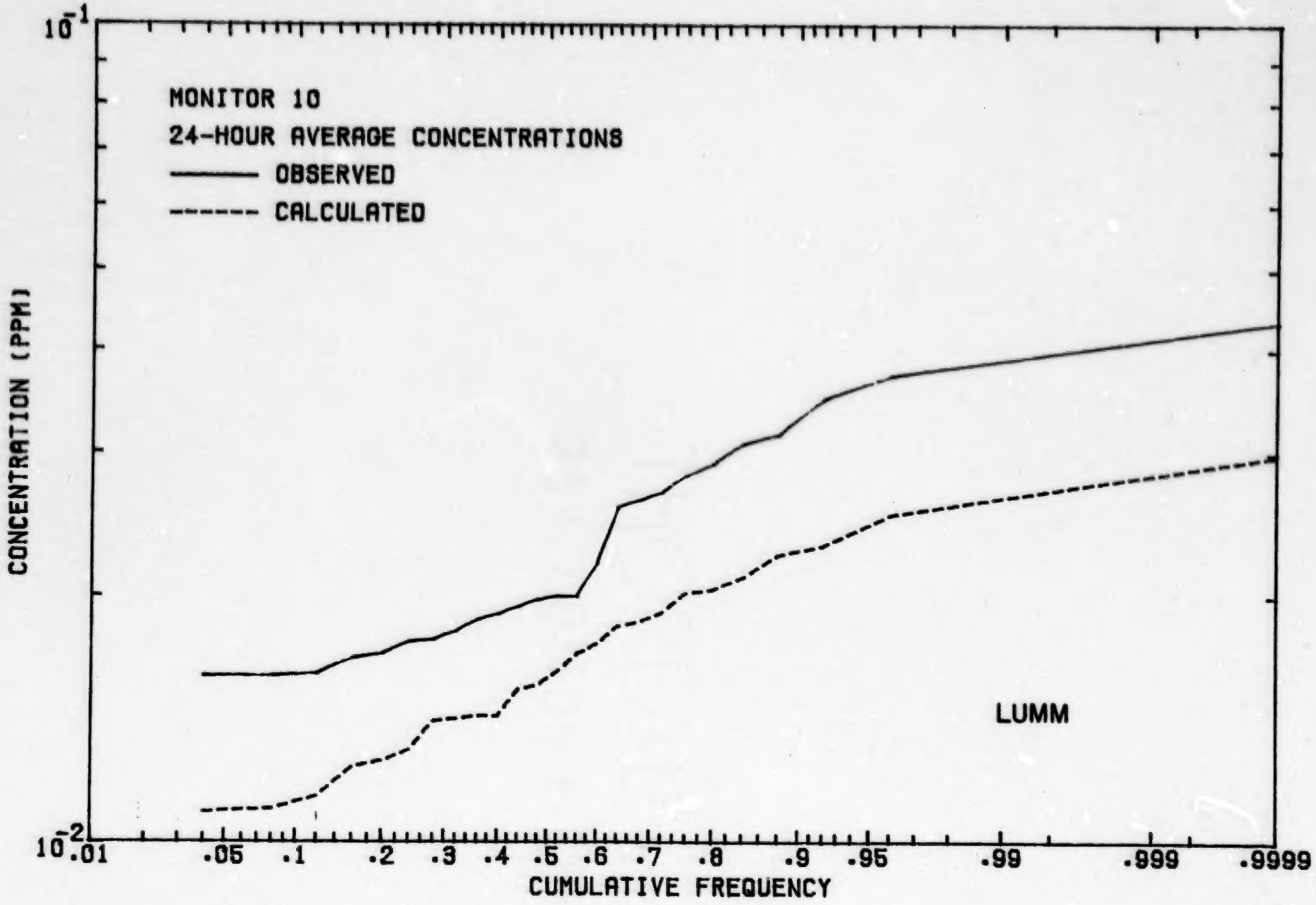

Figure E-27. Comparison of the cumulative frequency distribution of the 25 highest observed (minus background) 24-hour average SO_2 concentrations at Monitor 10 during the second year of the Westvaco monitoring program with the cumulative frequency distribution of the 25 highest 24-hour average concentrations calculated by LUMM.

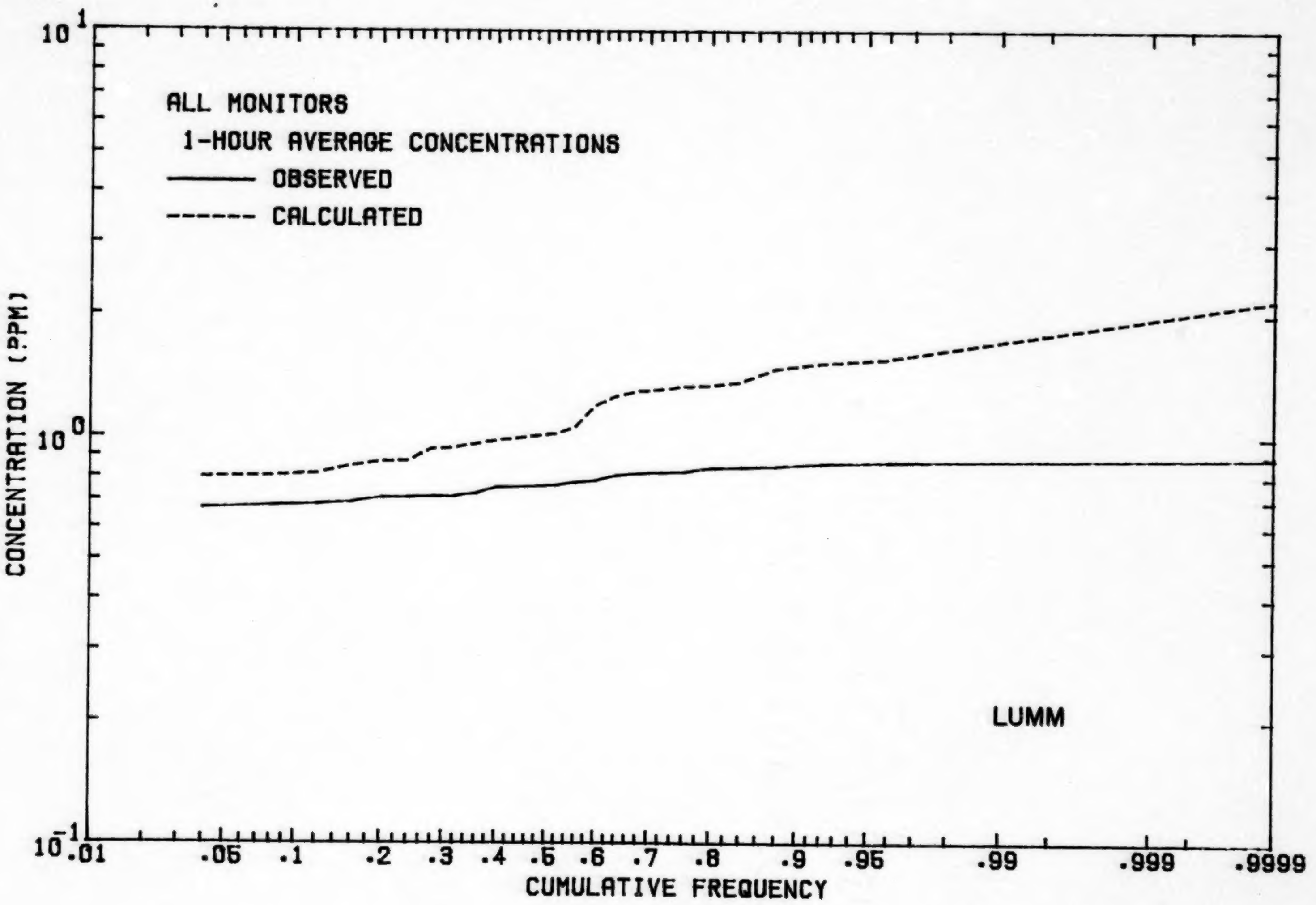

Figure E-28. Comparison of the cumulative frequency distribution of the 25 highest observed (minus background) 1-hour average SO_2 concentrations at all monitors during the second year of the Westvaco monitoring program with the cumulative frequency distribution of the 25 highest 1-hour average concentrations calculated by LUMM.

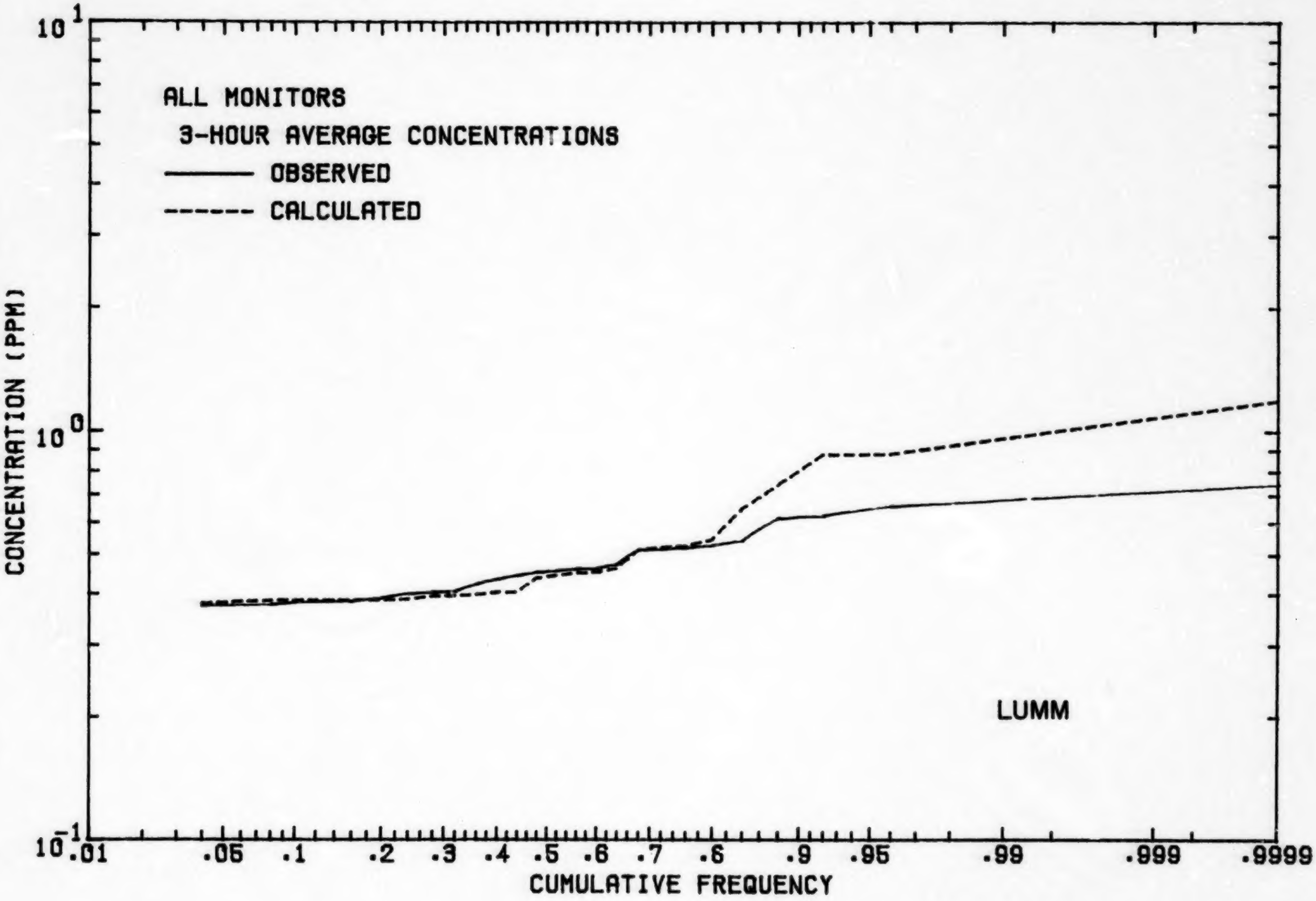

Figure E-29. Comparison of the cumulative frequency distribution of the 25 highest observed (minus background) 3-hour average SO_2 concentrations at all monitors during the second year of the Westvaco monitoring program with the cumulative frequency distribution of the 25 highest 3-hour average concentrations calculated by LUMM.

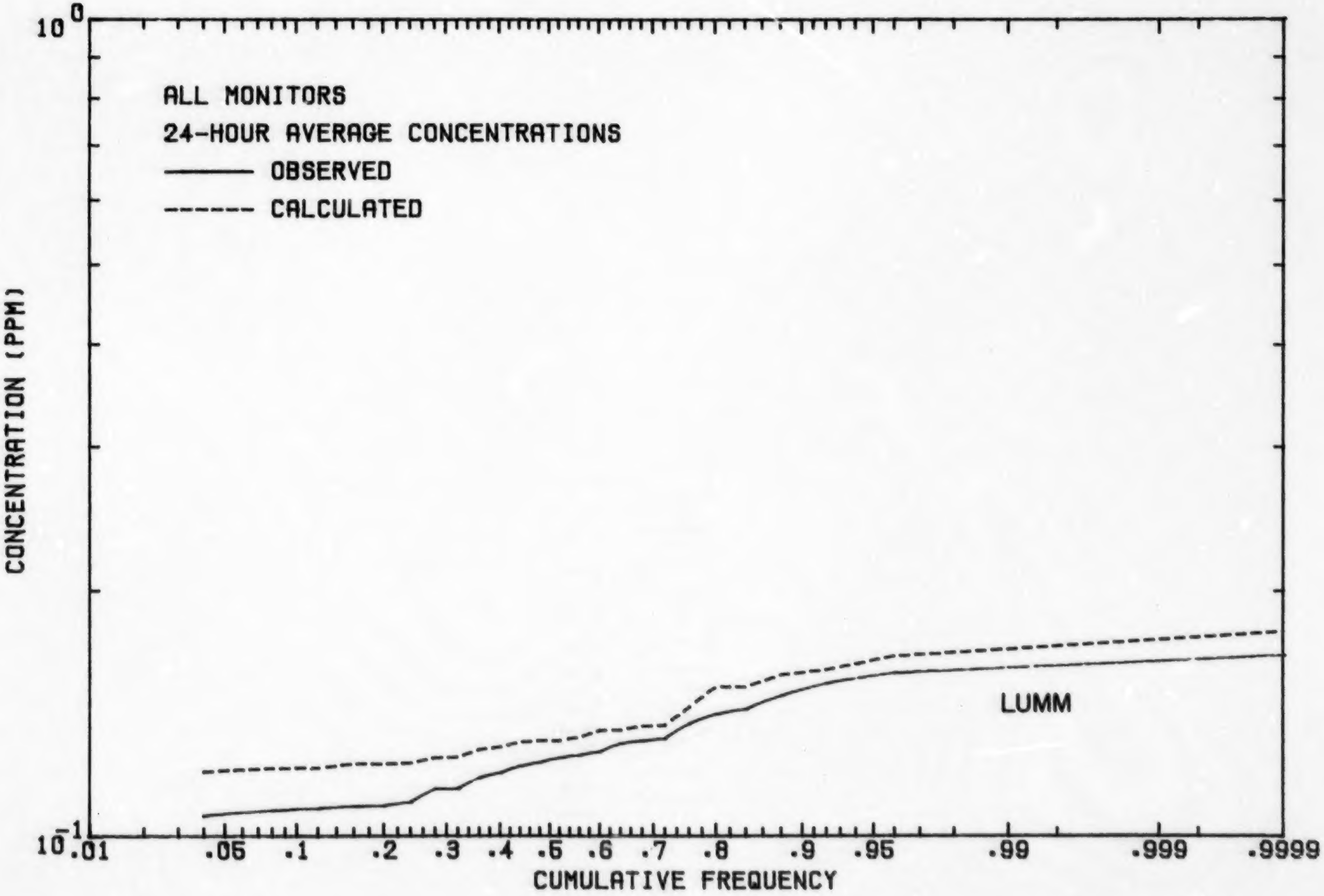

Figure E-30. Comparison of the cumulative frequency distribution of the 25 highest observed (minus background) 24-hour average SO_2 concentrations at all monitors during the second year of the Westvaco monitoring program with the cumulative frequency distribution of the 25 highest 24-hour average concentrations calculated by LUMM.

APPENDIX F

DESCRIPTION OF THE DISPERSION MODELS EVALUATED

F.1 DESCRIPTION OF THE SHORTZ MODEL

The SHORTZ model is a highly generalized dispersion model, based on the steady-state Gaussian plume concept, that is designed to calculate the short-term ground-level concentrations produced at a large number of receptors by emissions from multiple stack, building and area sources. The SHORTZ model was first used by Cramer, et al. (1975) to calculate the short-term air quality impacts of emissions from the major SO_2 sources located in and adjacent to Allegheny County, Pennsylvania. Subsequently, the SHORTZ model has been used in numerous dispersion model analyses throughout the United States, especially in areas of complex terrain (see Appendix H of Bjorklund and Bowers, 1982). A detailed technical discussion of the SHORTZ model and user's instructions for the SHORTZ computer code are contained in the report by Bjorklund and Bowers (1982). The following discussion considers only those features of the SHORTZ model applicable to the Westvaco model evaluation study.

Plume Rise Equations

The effective stack height H of a buoyant plume is given by the sum of the physical stack height h and the buoyant rise Δh. For an adiabatic or unstable atmosphere, the final buoyant rise Δh_N is given by

$$\Delta h_N = \left[\frac{1}{\bar{u}\ \{h\}} \left(\frac{3F}{2\gamma_1{}^2} \right)^{1/3} (10h)^{2/3} \right] f \qquad \text{(F-1)}$$

where the expression in the brackets is from Briggs (1969; 1971; 1972) and

$\bar{u}\{h\}$ = the mean wind speed at the stack height h (m/sec)

γ_1 = the adiabatic entrainment coefficient ~ 0.6 (Briggs, 1972)

F = the initial buoyancy flux (m^4/sec^3)

$$= \frac{gV}{\pi}\left(1 - \frac{T_a}{T_s}\right) \qquad \text{(F-2)}$$

V = the volumetric emission rate of the stack (m^3/sec)

$= \pi\, r^2\, w$

r = inner radius of stack (m)

w = stack exit velocity (m/sec)

g = the acceleration due to gravity (m/sec^2)

T_a = the ambient air temperature (°K)

T_s = the stack exit temperature (°K)

The factor f, which limits the plume rise as the mean wind speed at stack height approaches or exceeds the stack exit velocity, is defined by

$$f = \left\{\begin{array}{cl} 1 & ;\ \bar{u}\{h\} \le w/1.5 \\ \left(\dfrac{3w - 3\bar{u}\{h\}}{w}\right) & ;\ w/1.5 < \bar{u}\{h\} < w \\ 0 & ;\ \bar{u}\{h\} \le w \end{array}\right\} \qquad \text{(F-3)}$$

The Cramer, et al. (1975) stack-tip downwash correction factor f is generally not applied to stacks with Froude numbers less than about 3.0. The corresponding Briggs (1969; 1971; 1972) final rise formula for a stable atmosphere (potential temperature gradient greater than zero) is

$$\Delta h_s = \left\{ \begin{array}{ll} \left[\dfrac{6F}{\bar{u}\{h\} \gamma_2^{\;2}\, S} \right]^{1/3} & ;\ \pi\, \bar{u}\{h\}\, S^{-1/2} < 10h \\[2ex] \left[\dfrac{3F}{\bar{u}\{h\}\ \gamma_2^{\;2}\, S} \left(1 - \cos \left(\dfrac{10 S^{1/2}\ h}{\bar{u}\{h\}} \right) \right) \right]^{1/3} & ;\ \pi\, \bar{u}\{h\}\, S^{-1/2} \geq 10h \end{array} \right\} f \qquad \text{(F-4)}$$

where

γ_2 = the stable entrainment coefficient ~ 0.66 (Briggs, 1972)

$S = \dfrac{g}{T_a} \dfrac{\partial \theta}{\partial z}$

$\dfrac{\partial \theta}{\partial z}$ = vertical potential temperature gradient (°K/m)

The entrainment coefficients γ_1 and γ_2 are based on the suggestions of Briggs (1972). It should be noted that Equation (F-4) does not permit the calculated stable rise Δh_s to exceed the adiabatic rise Δh_N as the atmosphere approaches a neutral stratification ($\partial\theta/\partial z$ approaches 0). A procedure of this type is recommended by Briggs (1972).

Ground-Level Concentration Equations

The steady-state Gaussian plume equation used by the SHORTZ model to calculate the ground-level concentration at downwind distance x and crosswind distance y is

$$\chi\{x,y\} = \frac{KQ}{\pi \bar{u} H \sigma_y \sigma_z} \{\text{Vertical Term}\} \{\text{Lateral Term}\} \qquad \text{(F-5)}$$

where

K = scaling coefficient to convert input parameters to dimensionally consistent units

Q = source emission rate (mass per unit time)

$\bar{u}\{H\}$ = mean wind speed at the plume stabilization height H (m/sec)

σ_y, σ_z = standard deviations of the lateral and vertical concentration distributions at downwind distance x (m)

The Vertical Term refers to the plume expansion in the vertical or z direction and includes a multiple reflection term that limits plume growth to the surface mixing layer.

$$\{\text{Vertical Term}\} = \left\{ \exp\left[-\frac{1}{2}\left(\frac{H}{\sigma_z}\right)^2\right] + \sum_{n=1}^{\infty} \left[\exp\left[-\frac{1}{2}\left(\frac{2n\,H_m + H}{\sigma_z}\right)^2\right] + \exp\left[-\frac{1}{2}\left(\frac{2n\,H_m - H}{\sigma_z}\right)^2\right] \right] \right\} \qquad \text{(F-6)}$$

where H_m is the depth of the surface mixing layer. The exponential terms in the infinite series in Equation (F-6) rapidly approach zero near the source. At the downwind distance where the exponential terms exceed exp (-10) for n equal 3, the plume has become approximately uniformly mixed within the surface mixing layer. In order to shorten computer computation time without loss of accuracy, Equation (F-6) is changed to

$$\{\text{Vertical Term}\} = \frac{\sqrt{2\pi}\ \sigma_z}{2H_m} \tag{F-7}$$

beyond this point. Equation (F-7) changes the form of the vertical concentration distribution from Gaussian to rectangular. If H exceeds H_m, the Vertical Term is set equal to zero which results in zero values for the ground-level concentrations.

In complex terrain, the SHORTZ Vertical Term is modified by the use of effective plume stabilization heights and mixing depths under the following assumptions:

- The actual top of the surface mixing layer extends over the calculation grid at a constant height above mean sea level; the actual top of the surface mixing layer should not be confused with the effective top of the surface mixing layer, which is a mathematical device used to preclude violations of the Second Law of Thermodynamics when plumes pass over elevated terrain
- The axis of a plume contained within the surface mixing layer remains at the plume stabilization height above mean sea level, and the plume may impact elevated terrain within the surface mixing layer under stable, neutral or unstable conditions
- Plumes that stabilize above the top of the surface mixing layer do not contribute to significant ground-level concentrations at any receptor (this assumption also applies to flat terrain), including receptors that are above the top of the surface mixing layer

In order to determine whether the stabilized plume is contained within the surface mixing layer, it is necessary to calculate the mixing depth $H_m^*\{z_s\}$ at the source from the relationship

$$H_m^*\{z_s\} = H_m + z_a - z_s \tag{F-8}$$

where

H_m = the depth of the surface mixing layer measured at a point with elevation z_a above mean sea level (m)

z_s = the height above mean sea level of the source (m)

Equation (F-8) is represented schematically in Figure F-1, which assumes that z_a is the elevation of an airport. As shown by the figure, the actual top of the surface mixing layer is assumed to remain at a constant elevation above mean sea level. If the height H of the stabilized plume above the base of the stack is less than or equal to $H_m^*\{z_s\}$, the plume is defined to be contained within the surface mixing layer.

The height H_o of the stabilized plume above mean sea level is given by the sum of the height H of the stabilized plume above the base of the stack and the elevation z_s of the base of the stack. At any elevation z above mean sea level, the effective height H'{z} of the plume centerline above the terrain is then given by

$$H'\{z\} = \left\{\begin{matrix} H_o - z \ ; \ H_o - z \geq 0 \\ \\ 0 \ ; \ H_o - z < 0 \end{matrix}\right\} \tag{F-9}$$

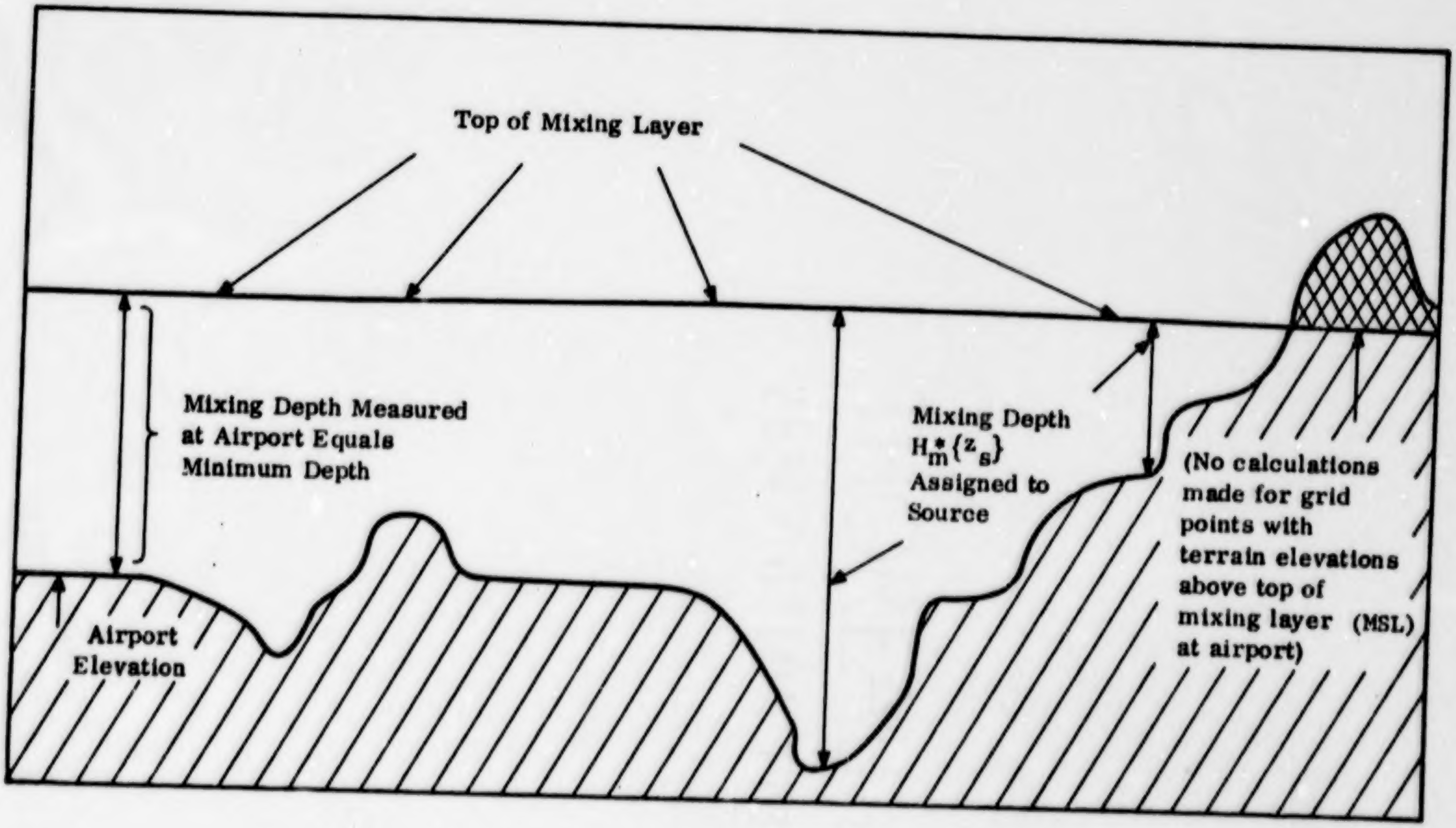
Top of Mixing Layer
Mixing Depth Measured at Airport Equals Minimum Depth
Mixing Depth $H_m^*\{z_s\}$ Assigned to Source
(No calculations made for grid points with terrain elevations above top of mixing layer (MSL) at airport)
Airport Elevation

FIGURE F-1. Mixing depth $H_m^*\{z_s\}$ used to determine whether the stabilized plume is contained within the surface mising layer.

The effective mixing depth $H_m'\{z\}$ above a point at elevation z above mean sea level is defined by

$$H_m'\{z\} = \left\{ \begin{array}{ll} H_m & ; z \geq z_a \\ H_m + z_a - z & ; z < z_a \end{array} \right\} \tag{F-10}$$

Figure F-2 illustrates the assumptions implicit in Equation (F-10). For grid points at elevations below the measurement base elevation (assumed in Figures F-1 and F-2 to be an airport), the effective mixing depth $H_m'\{z\}$ is allowed to increase in a manner consistent with Figure F-1. However, in order to prevent a physically unrealistic compression of plumes as they pass over elevated terrain, the effective mixing depth is not permitted to be less than the mixing depth measured at the airport. It should be emphasized that the concentrations are set equal to zero for grid points above the actual top of the mixing layer (see Figure F-1).

The Lateral Term refers to the crosswind expansion of the plume and is given by the expression

$$\{\text{Lateral Term}\} = \exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right] \tag{F-11}$$

where y is the crosswind distance from the plume centerline to the point at which concentration is calculated.

The SHORTZ model uses a wind-profile exponent law to adjust the observed mean wind speed from the measurement height to the stack height h for use in the plume rise calculations and to the plume stabilization height H for use in the concentration calculations. In complex terrain, the SHORTZ model assumes that the mean wind speed at any given height above

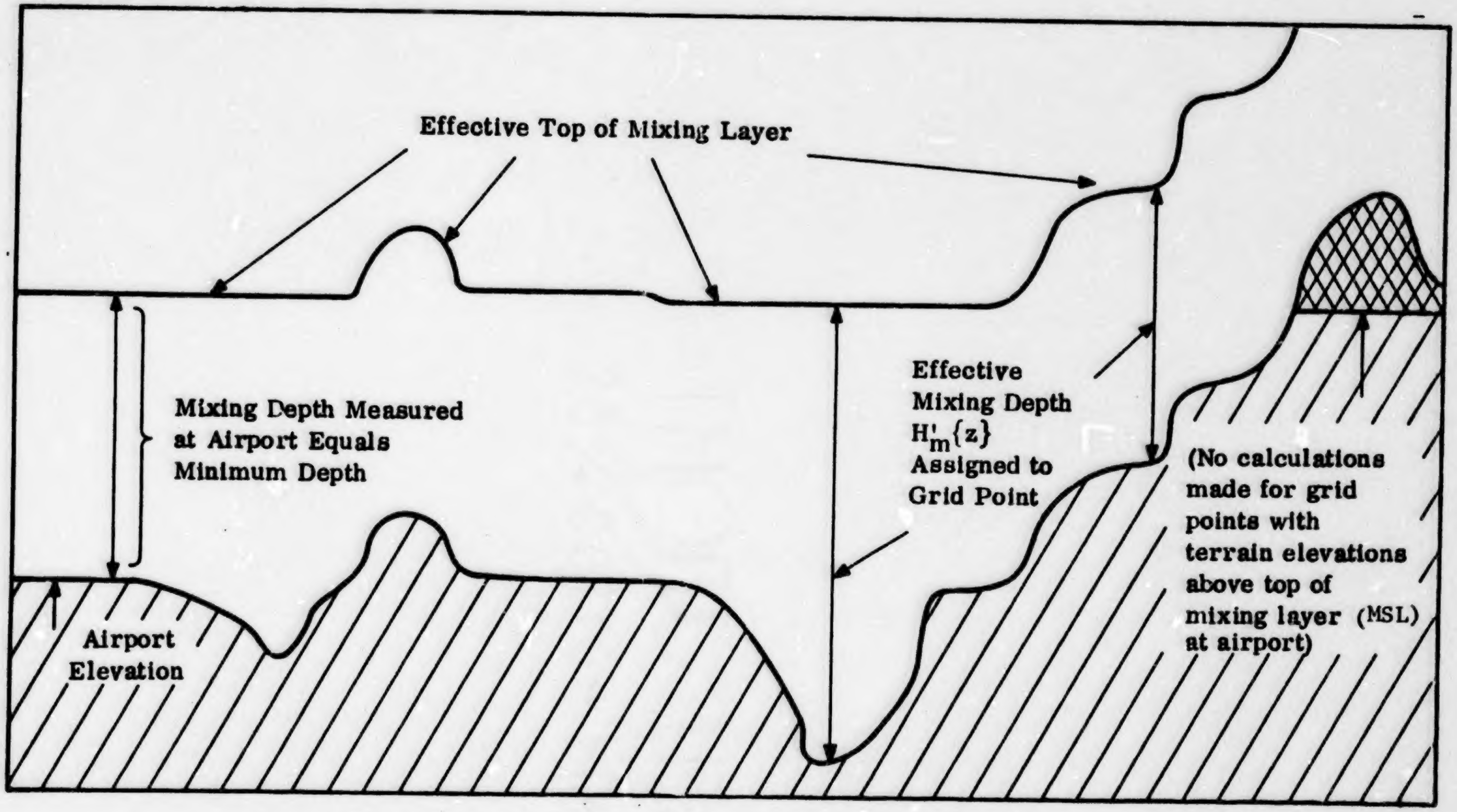
Effective Top of Mixing Layer
Mixing Depth Measured at Airport Equals Minimum Depth
Effective Mixing Depth $H'_m\{z\}$ Assigned to Grid Point
Airport Elevation
(No calculations made for grid points with terrain elevations above top of mixing layer (MSL) at airport)

FIGURE F-2. Effective mixing depth $H'_m\{z\}$ assigned to grid points for the concentration calculations.

mean sea level is constant. Thus, the mean wind speed $\bar{u}_R$ measured at a height z_R above the surface at a point with elevation z_a above mean sea level is adjusted to the stack height for the plume rise calculations by the relationship

$$\bar{u}\{h\} = \begin{Bmatrix} \bar{u}_R \left(\frac{h_o - z_a}{z_R} \right)^p & ; \; h_o \geq z_a + z_R \\ \\ \bar{u}_R & ; \; h_o < z_a + z_R \end{Bmatrix} \qquad \text{(F-12)}$$

where h_o is the height above mean sea level of the top of the stack and p is the wind-profile exponent. Similarly, the wind speed $\bar{u}\{H\}$ used in the concentration calculations is given by

$$\bar{u}\{H\} = \begin{Bmatrix} \bar{u}_R \left(\frac{H_o - z_a}{z_R} \right)^p & ; \; H_o \geq z_a + z_R \\ \\ \bar{u}_R & ; \; H_o < z_a + z_R \end{Bmatrix} \qquad \text{(F-13)}$$

Dispersion Coefficients

The SHORTZ model uses Cramer (1976) dispersion coefficients, which are of the form

$$\sigma_y\{x\} = \sigma_A' \cdot f_y\{x\} \cdot x \qquad \text{(F-14)}$$

and

$$\sigma_z\{x\} = \sigma_E' \cdot f_z\{x\} \cdot x \qquad \text{(F-15)}$$

where $\sigma_y (\sigma_z)$ is the lateral (vertical) dispersion coefficient, σ'_A (σ'_E) is the lateral (vertical) turbulent intensity or standard deviation of the wind azimuth (elevation) angle in radians and $f_y (f_z)$ is the lateral (vertical) "universal function." The generalized σ_y and σ_z equations used by the SHORTZ model include provisions for lateral and vertical virtual distances to account for the effects of entrainment on the initial dispersion of a buoyant plume.

Under the assumptions that σ_y is proportional to x over a distance x_{ry} downwind from an ideal point source and to x^α at longer downwind distances, Cramer, et al. (1972) derive the σ_y expression

$$\sigma_y\{x\} = \sigma'_A \, x_{ry} \left[\frac{x + x_y - x_{ry}(1-\alpha)}{\alpha x_{ry}} \right]^\alpha \qquad \text{(F-16)}$$

$$x_y = \begin{cases} \dfrac{\sigma_{yR}}{\sigma'_A} - x_R & ; \quad \dfrac{\sigma_{yR}}{\sigma'_A} \le x_{ry} \\[2ex] \alpha x_{ry} \left(\dfrac{\sigma_{yR}}{x_{ry} \, \sigma'_A} \right)^{1/\alpha} - x_R + x_{ry}(1-\alpha) & ; \quad \dfrac{\sigma_{yR}}{\sigma'_A} > x_{ry} \end{cases} \qquad \text{(F-17)}$$

where σ_{yR} is the lateral dispersion coefficient at downwind distance x_R. The SHORTZ model does not allow the lateral virtual distance x_y to be less than zero and, in the default mode, defines x_{ry} as 50 meters and α as 0.9.

As discussed in Appendix A, it has been the experience of the H. E. Cramer Company that the lateral "universal function" implicit in

Equation (F-16) adequately accounts for the effects of vertical wind-direction shear on lateral plume expansion in most situations (see Bjorklund and Bowers, 1982, p. 2-33). However, based on an examination of the hourly wind-direction and SO_2 concentration measurements from the first two quarters of the Westvaco monitoring program, the H. E. Cramer Company (January 1981) reported to EPA Region III that the plume from the Westvaco Main Stack is subject to very large vertical wind-direction shears as it rises through the highly channeled valley flow and enters the flow above the elevated terrain. Because of these large wind-direction shears, our January 1981 report suggested that it would be appropriate to modify SHORTZ for application to the Luke Mill by inclusion of the Cramer, et al. (1972) technique for accounting for the effects of vertical wind-direction shear on crosswind plume expansion. Following this approach, the total lateral dispersion coefficient σ_{yT} is given by

$$\sigma_{yT} = \left[\sigma_y{}^2 + \left(\frac{\Delta\theta' x}{4.3} \right)^2 \right]^{1/2} \qquad \text{(F-18)}$$

where σ_y is the unmodified SHORTZ lateral dispersion coefficient, x is the downwind distance and $\Delta\theta$ is the wind-direction shear in radians for the layer containing the plume. Equation (F-18) was used by the SHORTZ model in the Westvaco model performance evaluation described in Section 3.2.

The SHORTZ model assumes that, if a multiple reflection term (Equation (F-6)) is used to confine the plume within the surface mixing layer, σ_z may be assumed to be proportional to x at all downwind distances. The resulting σ_z expression is

$$\sigma_z\{x\} = \sigma_E' \left(x + x_z \right) \qquad \text{(F-19)}$$

$$x_z = \begin{cases} \dfrac{\sigma_{zR}}{\sigma_E'} - x_R & ; \quad \dfrac{\sigma_{zR}}{\sigma_E'} \geq x_R \\ \\ 0 & ; \quad \dfrac{\sigma_{zR}}{\sigma_E'} < x_R \end{cases} \tag{F-20}$$

where σ_{xR} is the vertical dispersion coefficient at downwind distance x_R.

Briggs (1972) notes that photographs of buoyant plumes show the radius to be approximately 0.5 times the plume rise. Under the assumption of Gaussian lateral and vertical concentration distributions at the downwind distance of final plume rise x_R, the SHORTZ model defines the lateral and vertical dispersion coefficients at this distance as

$$\sigma_{yR} = \sigma_{zR} = \frac{0.5\ \Delta h}{2.15} \tag{F-21}$$

The downwind distance to final rise x_R is given by

$$x_R = \begin{cases} 10h & ; \quad \dfrac{\partial\theta}{\partial z} \leq 0 \\ \\ \pi\ \bar{u}\{h\}\ S^{-1/2} & ; \quad \dfrac{\partial\theta}{\partial z} > 0 \text{ and } \pi\ \bar{u}\{h\}\ S^{-1/2} < 10h \\ \\ 10h & ; \quad \dfrac{\partial\theta}{\partial z} > 0 \text{ and } \pi\ \bar{u}\{h\}\ S^{-1/2} \geq 10h \end{cases} \tag{F-22}$$

F.2 DESCRIPTION OF THE VALLEY MODEL

The EPA Valley model (Burt, 1977) is primarily designed to calculate maximum 24-hour average ground-level concentrations produced by stack emissions in complex terrain. The Valley model is a screening model and is intended for use with hypothetical rather than actual meteorological inputs (Burt and Slater, 1977). The Valley model makes the "worst-case" assumptions that a plume in an elevated stable layer is confined within a 22.5-degree sector for 6 hours during a 24-hour period and that this plume directly impinges on any terrain at the height of the plume centerline. Common practice with the Valley model is to assume that the mean wind speed at plume height during the 6 hours of impingement is 2.5 meters per second and that the vertical dispersion in the elevated stable layer is equivalent to that predicted by the Pasquill-Gifford σ_z curve for F stability (Turner, 1969). The following description of the Valley model is of the version contained in the UNAMAP-4 series of models and used in the Westvaco model evaluation.

Plume Rise Equations

The Valley model uses the Briggs (1971; 1975) plume rise equations. At downwind distances less than the distance to final plume rise, plume rise is given by the adiabatic rise equation

$$\Delta h_N = \frac{1.6}{\bar{u}} F^{1/3} x^{2/3} \qquad \text{(F-23)}$$

If γ_1 in Equation (F-1) is set equal to the SHORTZ model's default value of 0.6 and the stack-tip downwash correction factor f is set equal to unity, Equations (F-1) and (F-23) are identical at a downwind distance of ten stack heights (10h). Under stable conditions, the plume rise given by Equation (F-23) is terminated in the Valley model when it equals the final plume rise predicted by the Briggs (1975) stable plume rise equation

$$\Delta h_s = 2.6 \left[\frac{F}{\bar{u}\ S} \right]^{1/3} \tag{F-24}$$

If γ_2 in Equation (F-4) is set equal to the SHORTZ model's default value of 0.66 and the downwash correction f is set equal to unity, the top line of Equation (F-4) is the same as Equation (F-24) except that the coefficient 2.6 in Equation (F-24) has a value of 2.4 in Equation (F-4). In other words, the final plume rise calculated by the Valley model under stable conditions exceeds the corresponding final plume rise calculated by the SHORTZ model by a factor of 1.08 (2.6/2.4). The Valley model assumes that the vertical potential temperature gradient with F stability is 0.035 degrees Kelvin per meter.

Ground-Level Concentration Equations

The Valley model gives the 24-hour average ground-level concentration attributable to 6 hours of plume impingement on elevated terrain under stable meteorological conditions as

$$\chi\{x\} = \frac{KQ}{2\sqrt{2\pi}\ \bar{u}\ \sigma_{zT}\ \Delta\theta'\ x} \exp\left[-\frac{1}{2}\left(\frac{H'}{\sigma_{zT}}\right)^2 \right] C\{z,H_o\} \tag{F-25}$$

where $\Delta\theta'$ is the sector width (0.3927 radians) within which the plume is assumed to be contained during the 6 stable hours. The effective plume height H' under stable conditions is given by

$$H'\{z\} = \begin{Bmatrix} H_o - z & ; & H_o - z \geq 10m \\ 10m & ; & H_o - z < 10m \end{Bmatrix} \tag{F-26}$$

Equations (F-9) and (F-26) are equivalent for all practical purposes except that Equation (F-9) is only used by the SHORTZ model when the plume is contained within the surface mixing layer. The correction $C\{z,H_o\}$, which reduces the calculated concentration to zero on terrain 400 meters or more above the plume centerline, is given by

$$C\{z,H_o\} = \frac{(401 - D\{z,H_o\})}{400} \tag{F-27}$$

where

$$D\{z,H_o\} = \begin{cases} z - H_o \; ; & 1 \le z - H_o \le 401\text{m} \\ 401 \; ; & z - H_o > 401\text{m} \end{cases} \tag{F-28}$$

Vertical Dispersion Coefficients

The Valley model requires only the vertical dispersion coefficient because emissions are assumed to be uniformly distributed in the horizontal within a 22.5-degree sector. The total vertical dispersion coefficient σ_{zT} is given by

$$\sigma_{zT} = \left[\sigma_z^{\,2} + (\Delta h/3.5)^2\right]^{1/2} \tag{F-29}$$

where σ_z is the Pasquill-Gifford vertical dispersion coefficient (Turner, 1969), represented in the Valley model by an equation of the form

$$\sigma_z = a\,x^b + c \tag{F-30}$$

The coefficients a, b and c in Equation (F-30) are functions of stability and downwind distance. The second term on the right hand side of Equation (F-29) is intended to account for the effects of entrainment ("bouyancy induced dispersion") on the initial vertical growth of a buoyant plume. The treatment of the effects of entrainment on initial plume growth in the SHORTZ and Valley models differs in two ways. First, the SHORTZ model assumes a Gaussian distribution of material at the distance of final rise, whereas the Valley model assumes a uniform ("top hat") distribution of material. Second, the SHORTZ model uses virtual distances to account for the enhanced initial growth of the plume, whereas the Valley model adds variances.

F.3 DESCRIPTION OF THE COMPLEX I AND COMPLEX II MODELS

The undocumented EPA Complex I and Complex II models were developed from the computer code for the EPA MPTER model (Pierce and Turner, 1980). The Complex I and II models are designed to use actual rather than hypothetical hourly meteorological inputs, and both models make stability-dependent assumptions about how complex terrain affects plume height above terrain. The primary difference between the two models is that the Complex I model assumes that emissions during each hour are uniformly distributed in the horizontal within a 22.5-degree sector, whereas the Complex II model assumes a Gaussian hourly crosswind concentration distribution. The following paragraphs describe the Complex I and II models as used in the Westvaco model evaluation study and recommend improvements to the models.

Plume Rise Equations

The Complex I and II models use the Briggs (1971; 1975) plume rise equations. If the Pasquill stability category is neutral (D) or unstable (A, B or C), both models assume an adiabatic thermal stratification and use Equation (F-23) to calculate plume rise as a function of downwind distance. Final plume rise is assumed to occur at the distance 3.5 x^* (Briggs, 1971) , where x^* is given by

$$x^* = \begin{cases} 14\ F^{5/8} & ;\ F \le 55\ m^4/sec^3 \\ 34\ F^{2/5} & ;\ F > 55\ m^4/sec^3 \end{cases} \qquad \text{(F-31)}$$

If the Pasquill stability category is stable, the Complex I and II models use Equation (F-23) to calculate distance-dependent plume rise with the final rise occurring at the distance where the plume rises given by Equations (F-23) and (F-24) are equal. The default vertical potential temperature gradients assumed by both models during hours of E and F stability are 0.020 and 0.035 degrees Kelvin per meter, respectively.

It should be emphasized that the official versions of the Complex I and II models key the selection of adiabatic or stable plume rise equation on the Pasquill stability category rather than on the vertical potential temperature gradient. Our analysis of the meteorological conditions during the periods with the highest observed SO_2 concentrations at the monitoring network on the elevated terrain in the sector southeast of the Westvaco Main Stack (see Figure 1-1) indicated that a stable thermal stratification usually is required for the plume centerline to be low enough for the plume to affect the monitoring network. Because the Pasquill stability categories indicated for the hours with high observed concentrations by objective stability classification schemes (for example, Turner, 1964) frequently were neutral or unstable, the Complex I and II models automatically assumed an adiabatic stratification which caused the models to overestimate plume rises and hence to underestimate the ground-level concentrations at the monitoring network. We therefore modified both models to read hourly values of the vertical potential temperature gradient and to key the selection of the adiabatic or stable plume rise equation on the potential temperature gradient, the same approach as used by the SHORTZ model. Additionally, we added logic to ensure that the calculated stable plume rise did not exceed the corresponding calculated adiabatic plume rise.

Ground-Level Concentration Equations

The Complex I model assumes that the plume is uniformly distributed in the horizontal within a 22.5-degree sector during each hour. The ground-level concentration at downwind distance x within this sector is given by

$$\chi\{x\} = \frac{2KQ}{\sqrt{2\pi}\ \bar{u}\{h\}\ \sigma_{zT}\ \Delta\theta'\ x}\ \{\text{Vertical Term}\} \qquad \text{(F-32)}$$

If only the first term of the full Vertical Term given by Equation (F-6) is considered under stable conditions, Equation (F-32) has the same form as the corresponding equation for the Valley model (Equation (F-25)) except that Equation (F-32) has not been divided by a factor of 4 to account for the Valley model's assumptions that essentially the same hourly concentration occurs during 6 hours of a 24-hour period. The Complex II model gives the hourly ground-level concentration at downwind distance x and crosswind distance y as

$$\chi\{x,y\} = \frac{KQ}{\pi\ \bar{u}\{h\}\ \sigma_{zT}\ \sigma_{yT}}\ \{\text{Vertical Term}\}\ \{\text{Lateral Term}\} \qquad \text{(F-33)}$$

The Complex I and II models assume that the mixing height H_m is infinite with E or F stability and is terrain following with A, B, C or D stability. Both models define the effective plume height H' as

$$H' = \mathrm{MAX}\left\{FH,\ H - (1-F)(H_o - z)\right\} \qquad \text{(F-34)}$$

where the "plume path coefficient" F is assumed to be 0.5 for the unstable (A, B and C) and neutral (D) Pasquill stability categories and to be zero for the stable (E and F) Pasquill stability categories. Thus, the Complex I and II models make the same basic assumption about plume height above terrain under stable conditions as the Valley model. For consistency with the Valley model, the Complex I and II models do not allow H' to be less than 10 meters.

The Complex I and II models assume that wind speed is a function of height above local ground level (rather than above mean sea level as assumed by the SHORTZ model). The wind speed $\bar{u}_R$ measured at height z_R is adjusted to the stack height h for use in both the plume rise and concentration calculations by the expression

$$\bar{u}\{h\} = \bar{u}_R \left(\frac{h}{z_R}\right)^p \tag{F-35}$$

where the wind-profile exponent p is assigned on the basis of the Pasquill stability category.

The Complex I and II models accept sequential hourly emission rates and calculate hourly stack exit velocities from a single input exit velocity under the assumption that the exit velocity is directly proportional to the emission rate. Because of variations in coal-sulfur content, this approximation is not highly accurate for the Westvaco Main Stack. Also, the Complex I and II models do not allow for hour-to-hour variations in the stack exit temperature. We therefore modified the computer codes for the two models to allow them to accept hourly values of the stack exit velocity and exit temperature.

Dispersion Coefficients

The Complex I and Complex II models use Equation (F-29) to calculate the total vertical dispersion coefficient, with the Pasquill-

Gifford vertical dispersion coefficient σ_z represented by an equation of the form

$$\sigma_z = \alpha x^\beta \qquad \text{(F-36)}$$

rather than of the form of Equation (F-30). The coefficients α and β in Equation (F-36) are functions of stability and downwind distance. The Complex I model does not require lateral dispersion coefficients because of the sector-averaging assumption. The Complex II model defines the total lateral dispersion coefficient σ_{yT} as

$$\sigma_{yT} = \left[\sigma_y^2 + (\Delta h/3.5)^2\right]^{1/2} \qquad \text{(F-37)}$$

where σ_y is the Pasquill-Gifford lateral dispersion coefficient, represented by equations of the form

$$\sigma_y = 465 \cdot x \cdot \tan(TH) \qquad \text{(F-38)}$$

$$TH = 0.01745 \left(d - e \, \ell n(x)\right) \qquad \text{(F-39)}$$

The coefficients d and e in Equation (F-39) are functions of stability. The second term on the right-hand side of Equation (F-37) is intended to account for the effects of entrainment on lateral plume growth.

F.4 DESCRIPTION OF THE LUMM MODEL

The Luke Mill Model (LUMM) is a single-source model that was developed by Hanna, et al. (1982a) for application to the Westvaco Main Stack. The LUMM and SHORTZ models are qualitatively similar in that both models use direct turbulence measurements to predict plume expansion, both models attempt to account for the effects of vertical wind-direction shear on lateral plume growth, and both models key the selection of the appropriate plume rise equation on the vertical potential temperature gradient. Also, both the LUMM and SHORTZ models utilize onsite meteorological measurements to the maximum extent possible. Hanna, et al. (1982a) evaluated the performance of six versions of the LUMM model, two of which differed only in meteorological inputs. The version of the LUMM model considered by Hanna, et al. (1982a) to give the best overall performance (Model 4) is briefly described below.

Plume Rise Equations

The LUMM model considers only two stabilities: (1) stable, and (2) "neutral" (adiabatic or unstable). If the vertical potential temperature gradient is positive, the final plume rise is given by Equation (F-24). To ensure that the stable plume rise Δh_S does not exceed the corresponding adiabatic plume rise Δh_N, the LUMM model also uses Equations (F-23) and (F-31) to calculate Δh_N for hours with stable (positive) potential temperature gradients. Neutral conditions are assumed if Δh_N is less than Δh_S or if the potential temperature gradient is less than or equal to zero. Otherwise, stable conditions are assumed.

Ground-Level Concentration Equations

During hours with neutral conditions, the LUMM model uses Equation (F-33) to calculate the ground-level concentration at downwind distance x and crosswind distance y except that only the first term of the generalized Vertical Term (see Equation (F-6)) is used by the LUMM model. That is, the multiple reflection portion of the Vertical Term that confines the plume within the surface mixing layer is not incorporated in the LUMM model. The effective plume height H' under neutral conditions is given by Equation (F-34) with the "plume path coefficient " F set equal to 0.4 to fit the observations at the Luke Mill (Hanna, et al., 1982a, p. 5-7). Unlike the SHORTZ, Complex I and Complex II models, the LUMM model does not use a wind-profile exponent law to extrapolate the wind speed from the measurement height to the stack or plume height. Instead, the LUMM model estimates the appropriate wind speeds from the onsite tower wind measurements (see Table A-1 of Hanna, et al., 1982a).

During hours with stable conditions, the effective plume height assumed by the LUMM model depends on the relationship between the plume height above plant grade and the height of a critical streamline H_c above plant grade. The critical streamline height is given by

$$H_c = \Delta z_{max}(1 - Fr) \qquad \text{(F-40)}$$

where the Froude number is defined as

$$Fr = \frac{\bar{u}}{\Delta z_{max} \; S^{1/2}} \qquad \text{(F-41)}$$

and Δz_{max} is (Hanna, et al., 1982a, p. 5-8) the "maximum mountain height above the stack base in the direction of interest within about 10 km of the stack." If H is greater than H_c, the ground-level concentration is calculated from Equation (F-33), with H' given by Equation (F-34). If H is less than H_c and the receptor is below H_c, two concentrations are calculated. The first concentration is given by Equation (F-33) with H' redefined as

$$H' = \mathrm{MAX}\left\{0,\ H_o - z\right\} \qquad \text{(F-42)}$$

The second concentration calculated under stable conditions when H is less than H_c is

$$\chi = \frac{RKQ}{2\pi\ \bar{u}\ \sigma_{yT}\ \sigma_{zT}} \exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_{yT}}\right)^2\right] \qquad \text{(F-43)}$$

The reflection coefficient R in Equation (F-43) is set equal to 1.2 in the LUMM model because Hanna, et al. (1982a) consider this value to be "appropriate for terrain slopes of about 20 to 30° encountered in the area surrounding the Luke Mill." The minimum of the two concentrations calculated when H is less than H_c is assumed by the LUMM model to be the correct concentration. Additionally, if a receptor is above H_c and H is below H_c, the concentration at the receptor is assumed to be zero (Hanna, 1982).

Dispersion Coefficients

The LUMM model's total lateral dispersion coefficient σ_{yT} is of the form

$$\sigma_{yT} = \left[\sigma_y^2\{\text{turbulence}\} + \sigma_y^2\{\text{buoyancy}\} + \sigma_y^2\{\text{wind shear}\}\right]^{1/2} \qquad \text{(F-44)}$$

Similarly, the LUMM model's total vertical dispersion coefficient σ_{zT} is of the form

$$\sigma_{zT} = \left[\sigma_z{}^2\{\text{turbulence}\} + \sigma_z{}^2\{\text{buoyancy}\}\right]^{1/2} \tag{F-45}$$

The turbulence contributions to σ_{yT} and σ_{zT} are given by

$$\sigma_y\{\text{turbulence}\} = I_y \cdot f_y\{x\} \cdot x \tag{F-46}$$

$$\sigma_y\{\text{turbulence}\} = I_z \cdot f_z\{x\} \cdot x \tag{F-47}$$

where I_y and I_z are the lateral and vertical turbulent intensities, respectively. (The lateral turbulent intensity I_y in Equation (F-45) corresponds to σ'_A in Equation (F-14), while the vertical turbulent intensity I_z in Equation (F-47) corresponds to σ'_E in Equation (F-15).) Comparison of Equations (F-46) and (F-47) with Equations (F-14) and (F-15) shows that the turbulence-induced components of the dispersion coefficients used by the LUMM and SHORTZ models are based on the same concepts. However, the two models differ in the assumed forms of the "universal functions" f_y and f_z.

The "universal functions" used by the LUMM model were inferred from the equations proposed by Briggs (1973) for rural dispersion coefficients. The lateral "universal function" for both neutral and stable conditions is defined in the LUMM model as

$$f_y\{x\} = (1 + 0.0001x)^{-1/2} \qquad \text{(F-48)}$$

The vertical "universal function" varies with stability and wind speed in the LUMM model and is given by

$$f_z\{x\} = \left\{ \begin{array}{ll} 1.0 & ; \text{ neutral and } \bar{u} < 8 \text{ m/sec} \\ (1 + 0.0003x)^{-1} & ; \text{ stable and } \bar{u} < 8 \text{ m/sec} \\ (1 + 0.0015x)^{-1/2} & ; \ \bar{u} \geq 8 \text{ m/sec} \end{array} \right\} \qquad \text{(F-49)}$$

The LUMM, Valley, Complex I and Complex II models all assume a uniform ("top hat") concentration distribution for the plume at the downwind distance of final plume rise. Additionally, all four models include the effects of entrainment by the buoyant plume ("buoyancy induced dispersion") by adding variances. However, the buoyancy contribution assumed by the LUMM model, which is given by

$$\sigma_y\{\text{buoyancy}\} = \sigma_z\{\text{buoyancy}\} = 0.4\ \Delta h \qquad \text{(F-50)}$$

is a factor of 1.4 larger than assumed by the three other models.

The LUMM model assumes that the contribution of vertical wind-direction shear to lateral plume expansion is given by

$$\sigma_y\{\text{wind shear}\} = 0.34\ \Delta\theta'\ x \qquad \text{(F-51)}$$

This expression is the same as used by the SHORTZ model (see Equation (F-18)) except that the LUMM model's shear coefficient of 0.34 is a factor of 1.46 larger than the SHORTZ model's shear coefficient. The first version of the LUMM model assumed a shear coefficient of 0.17 on the basis of suggestions made by Pasquill (1976). Although there are theoretical arguments in support of the doubling of the shear coefficient in the subsequent versions of the LUMM model, this doubling was also required to fit the LUMM model to the Westvaco data set (Hanna, 1982).

As noted above, the LUMM model does not include the multiple reflection portion of the full Vertical Term (see Equation (F-6)) to confine the plume within the surface mixing layer. To avoid underestimation of concentrations at downwind distances where the effects of the restriction on vertical mixing at the top of the surface mixing layer begin to affect ground-level concentrations, the LUMM model does not allow the total vertical dispersion coefficient σ_{zT} to exceed 340 meters. The first two versions of the LUMM model, which did not allow σ_z to exceed 136 meters, systematically underestimated the concentrations observed at Monitor 10 (the Stony Run monitor in Figure 1-1) because a larger σ_z was required to mix the plume downward to this monitor (Hanna, 1982).